# TeV Emission from the Plerion formed by the Massive Black Hole at the Galactic Center

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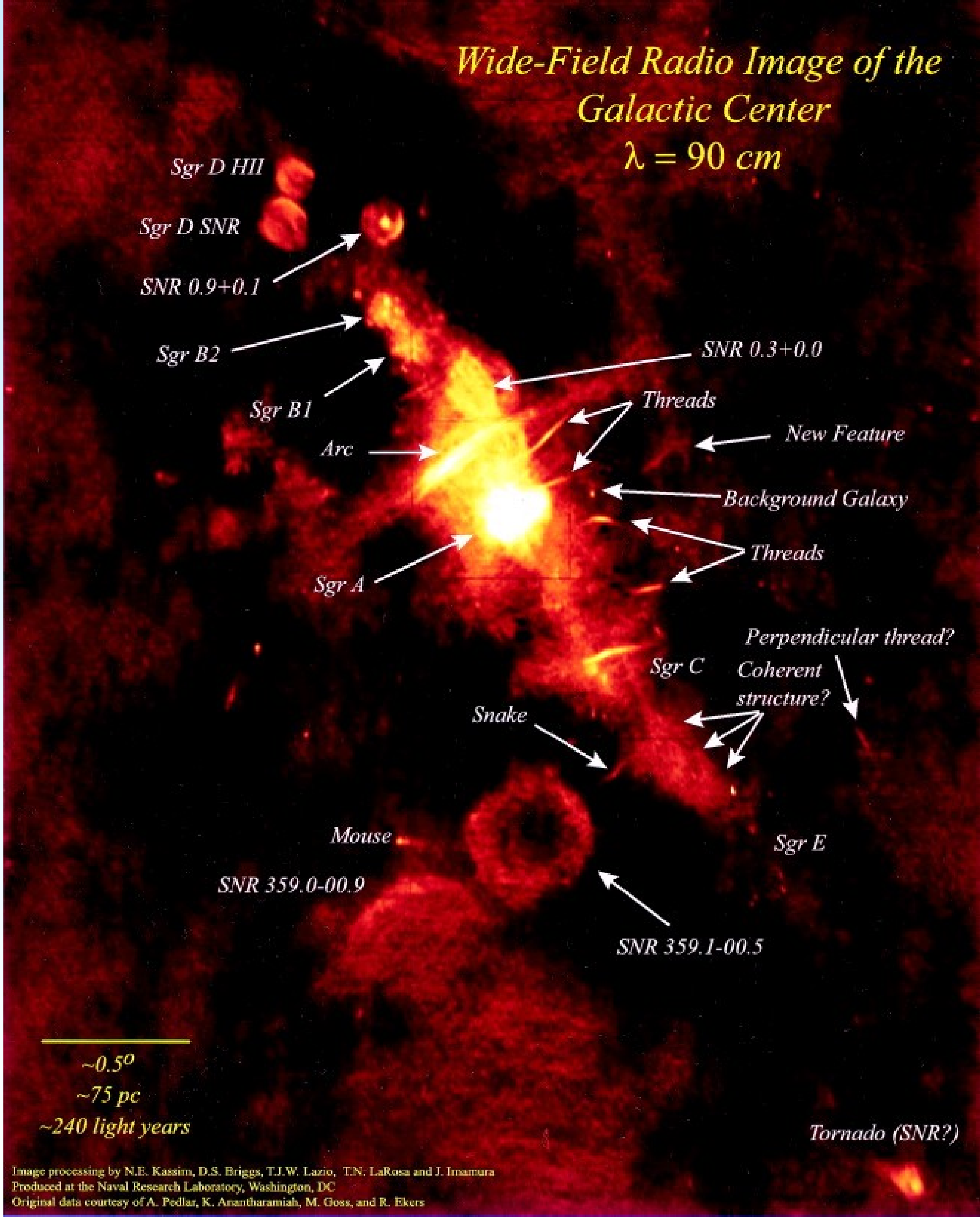
# Galactic Center Region at 90 cm (330 MHz)

- Nonthermal radio-emitting filaments features
- Large scale magnetic fields and relativistic electrons
- SNRs, HII regions
- Poloidal magnetic field within ~100 pc of nucleus
- Sgr A*: compact radio sources at nucleus of Milky Way

LaRosa et al. (2000)

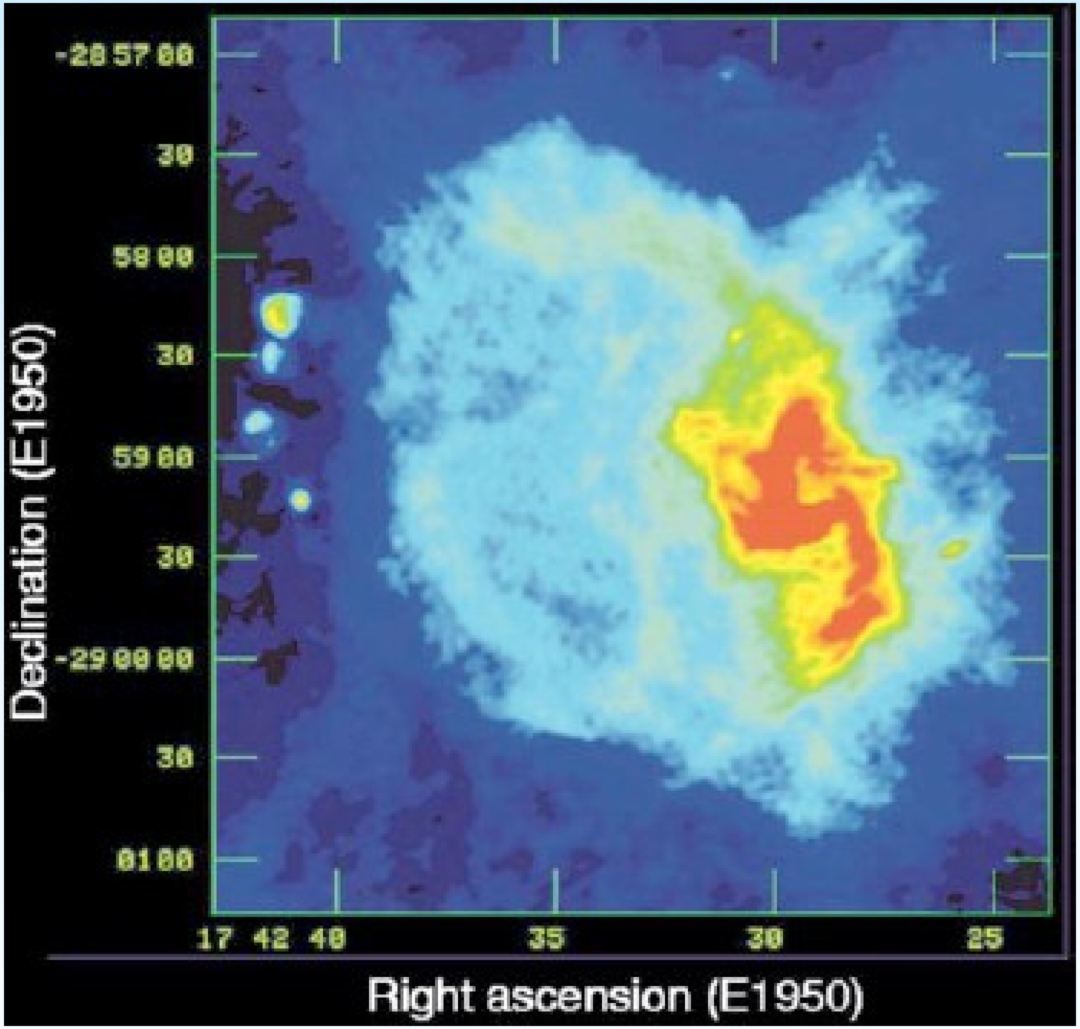


# Inner Sagittarius region (4 ´×3 ▯, or 9.3×7 pc)

**Sgr A East** (blue): extremely energetic ($\approx 10^{52}$ ergs) region occurring ≈ 50,000 yrs ago from chain of SNRs, a GRB, or star swallowed by BH. Diffuse X-ray emission.

**Sgr A West** (red): Gas and dust streamers ionized by stars and spiraling around the Galactic center, possibly feeding the nucleus.

**Sgr A*:** A bright compact radio source at intersection of the arms of the Sgr A West



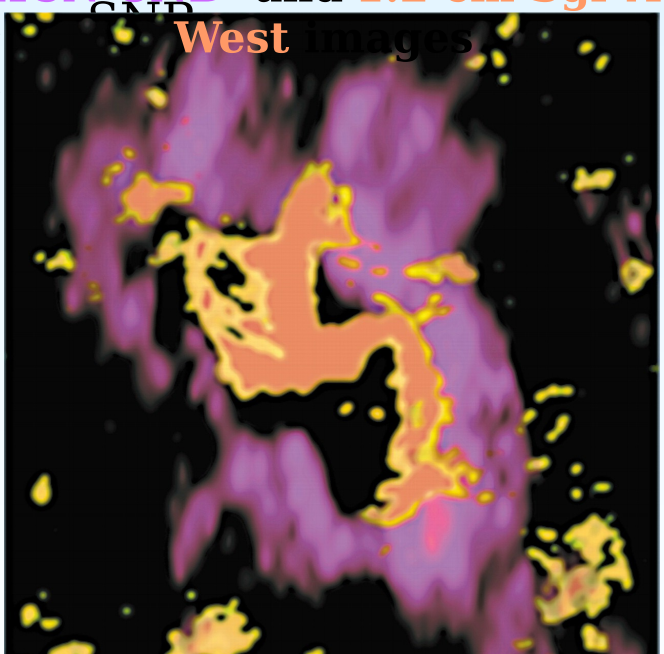

**6 cm VLA radio of Sgr A East and Sgr A West**

(Yusef-Zadeh, Melia, & Wandle 2000)

## Inner few parsecs

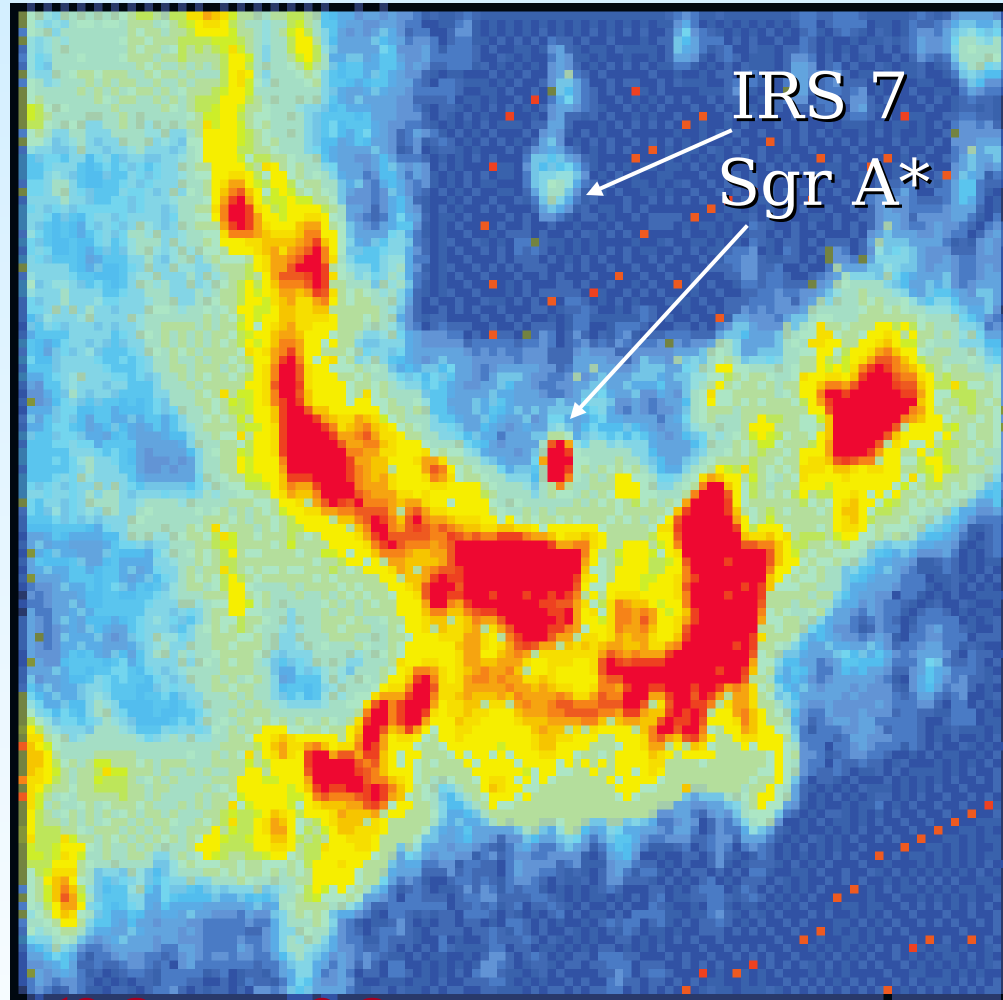
1. Molecular dusty ring (circumnuclear disk: CND)
2. Three-arm spiral of ionized gas and dust streamers (Sgr A West)
3. Evolved and young star clusters
4. Diffuse hot gas
5. SNR
6.

**HCN CND and 1.2 cm Sgr A West images**



(Wright et al. 1993) **(4 pc × 4 pc )**

**2 cm VLA radio of Sgr A**




**(0.8 pc × 0.8 pc )**

(Yusef-Zadeh & Wardle 1993)

# Massive Black Hole at the Center of the Milky Way Galaxy

IR (K-band) observations of stellar radial velocities

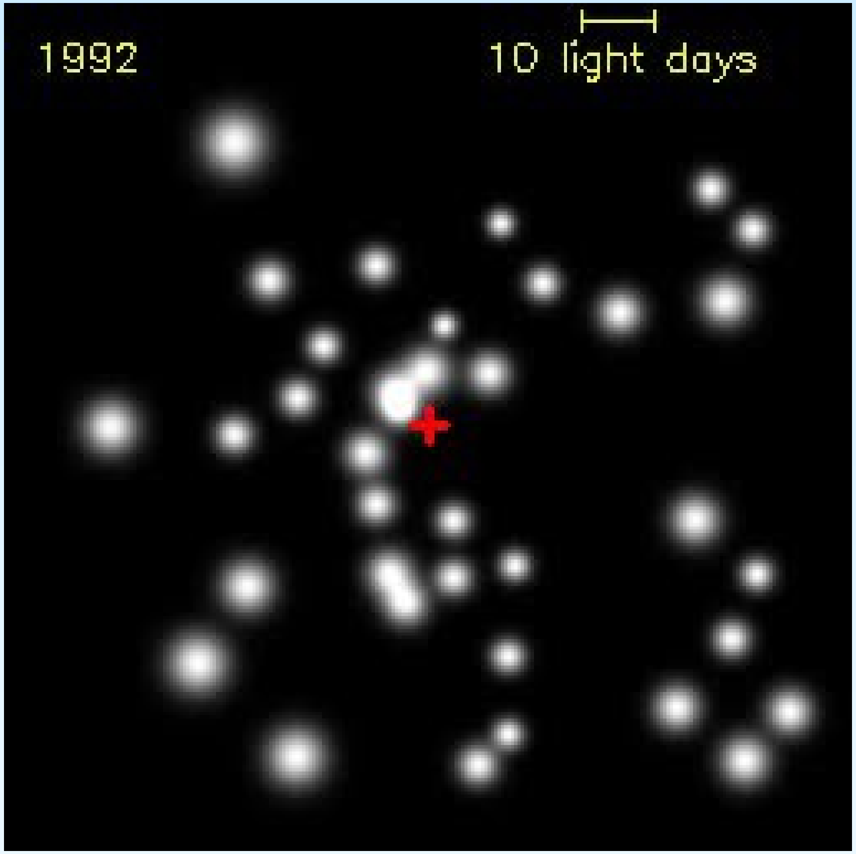
1 arcsec = 0.04 pc = 46 lt-days ($d_{GC}$ = 8 kpc)

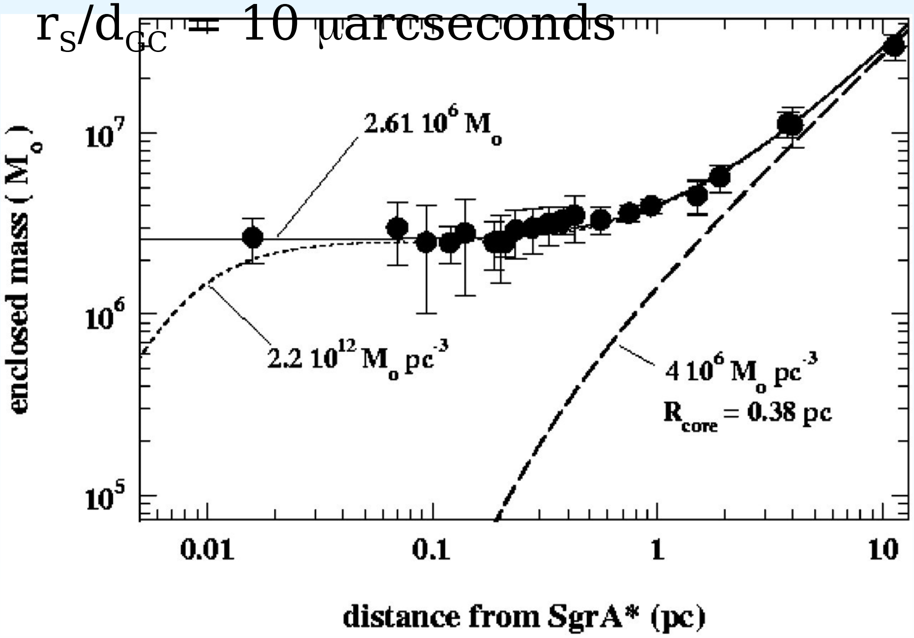
NIR speckle imaging techniques

Mass within 0.015 pc $\approx 4\times10^6$ $M_\odot$

$$r_S = \frac{2GM}{c^2} = 1.2\times10^{12}\left(\frac{M_{BH}}{4\times10^6 M_o}\right) cm$$

$r_S/d_{GC}$ = 10 μarcseconds




R. Genzel, et al. (2004)

Eddington luminosity:

$$L_{Edd} = \frac{4\pi G M m_H}{\sigma_T} = 5\times10^{44}\left(\frac{M_{BH}}{3\times10^6 M_o}\right) erg s^{-1}$$

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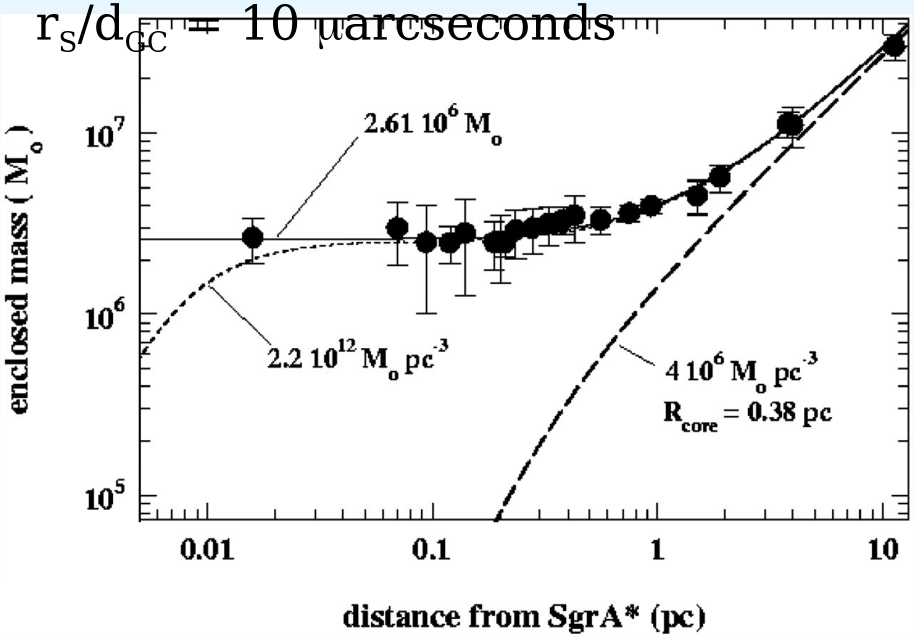


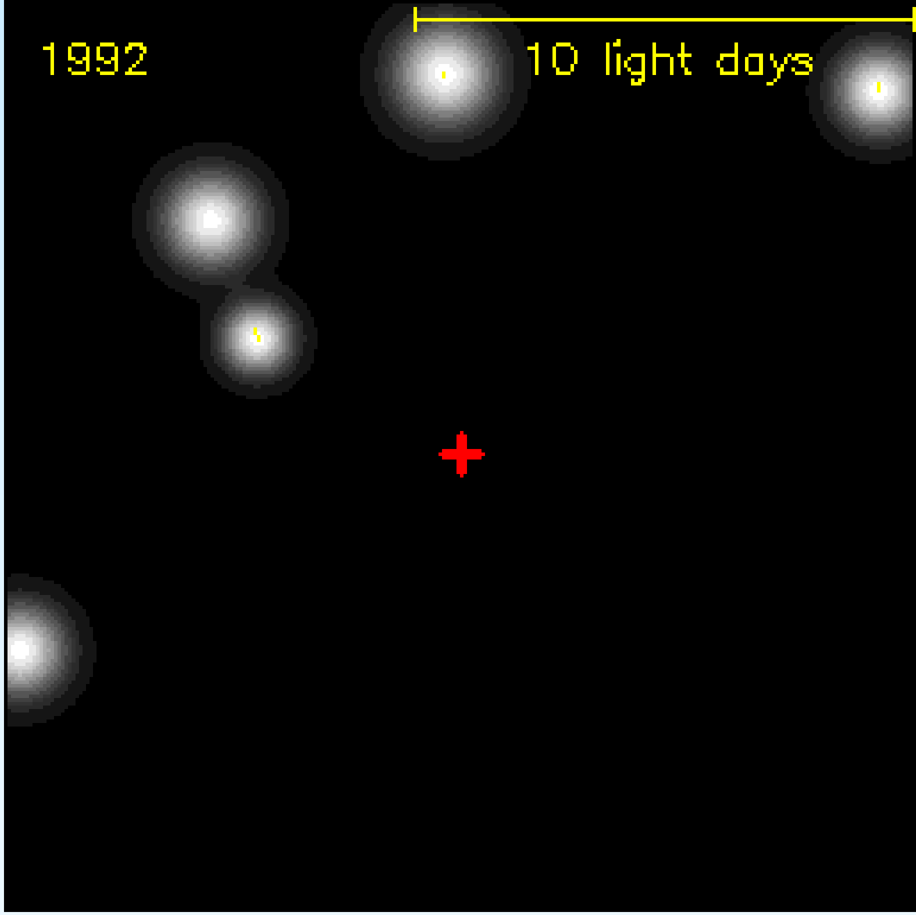


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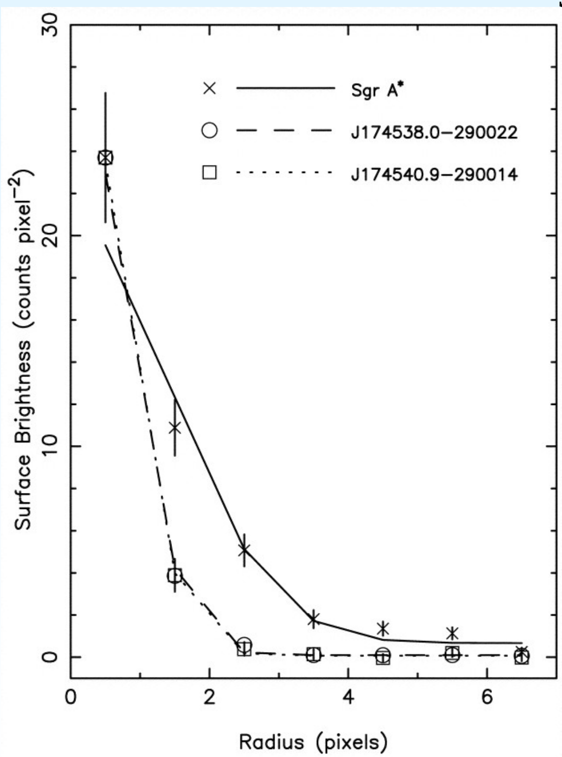
## Quiescent X-ray Emission from Sgr A* **(3.5 pc × 3 pc )**

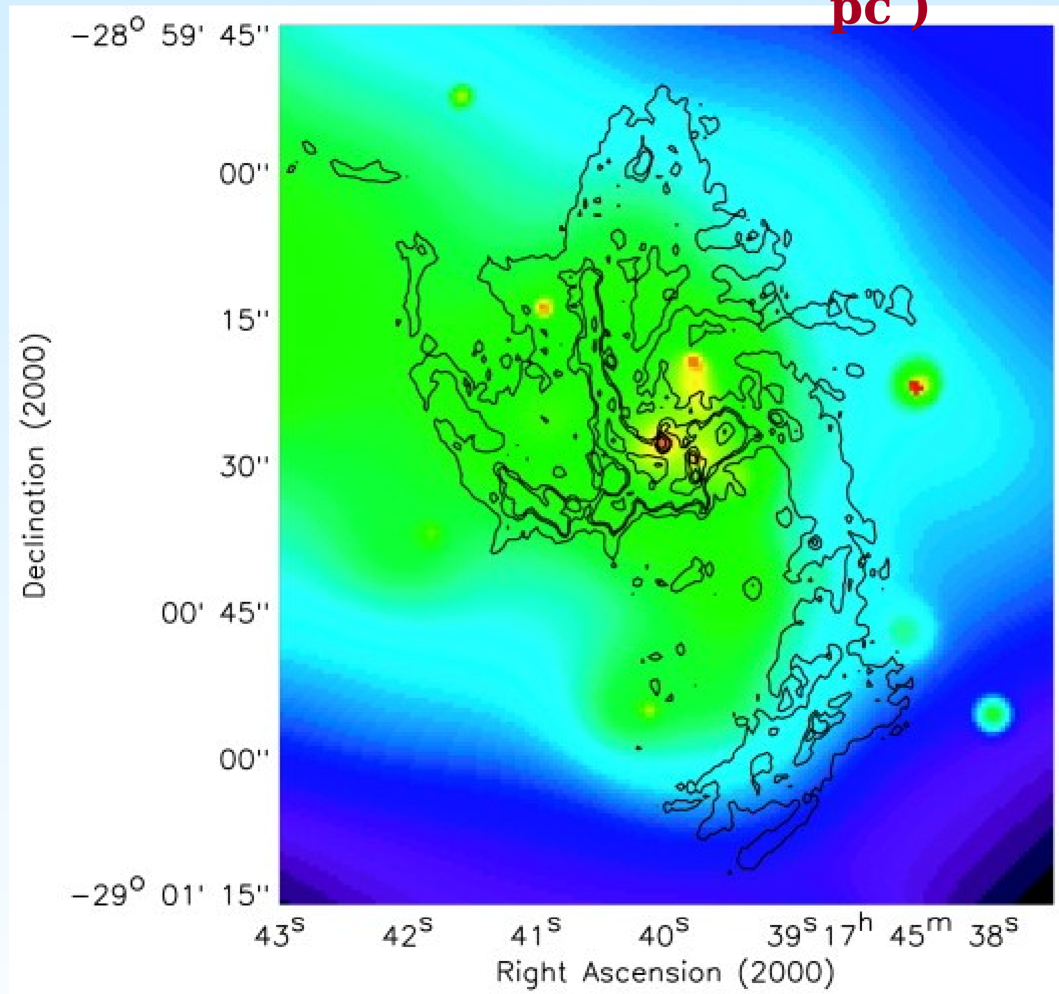
X-rays exhibit two different states:

1. Weak quiescent X-ray emission from an extended region

   ⇒ size of 0.6 arcseconds, or $7\times10^{16}$ cm ≈ $10^5$ $r_S$

   $.0^{33}$



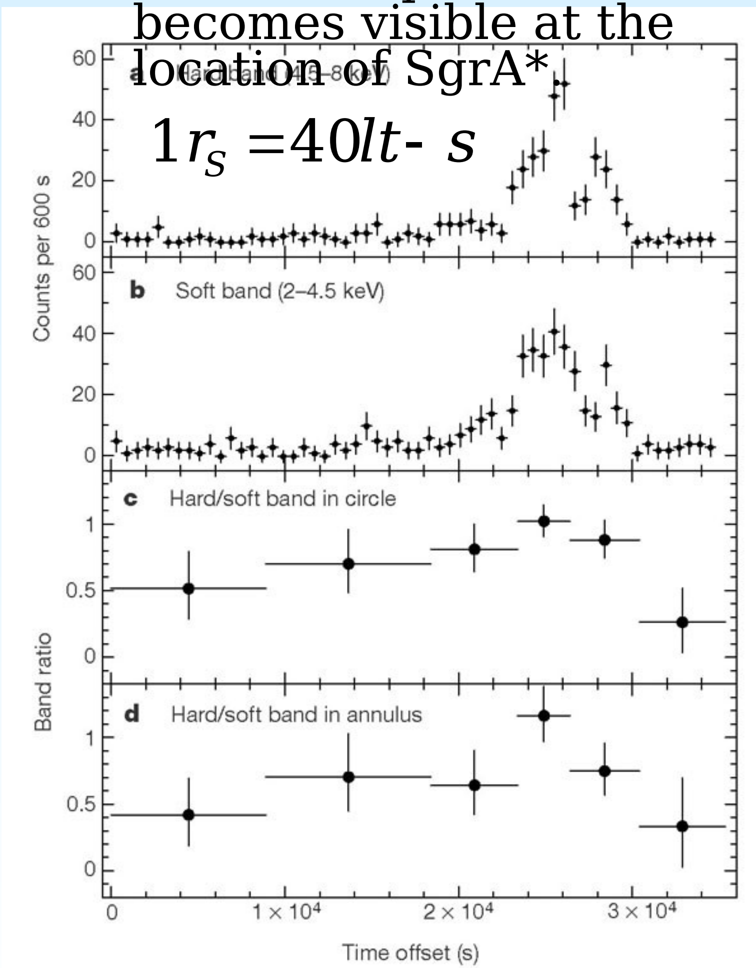




0.5-7 keV Chandra X-ray image overlaid on 6 cm radio image (Baganoff et al. 2003)

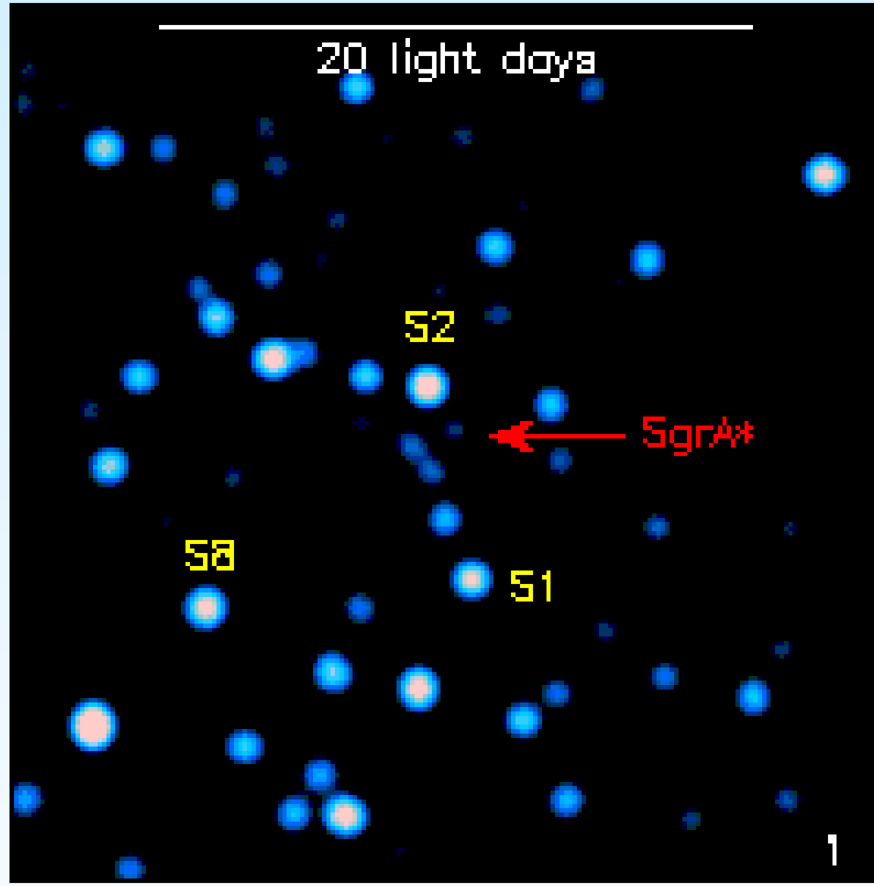
## Flaring X-ray Emission from Sgr A*

2. X-ray flares with a period of about one per day, rising by factors up to 100 during several tens of minutes. A distinctive point source becomes visible at the location of SgrA*.

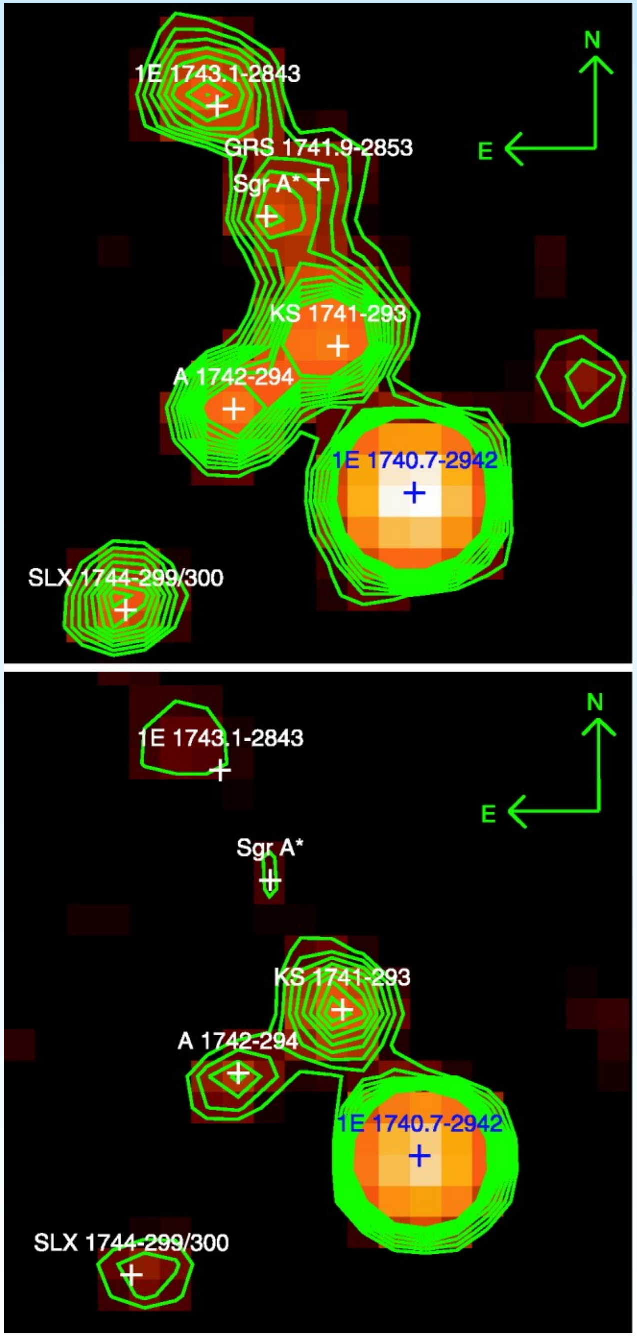
$$1 r_S = 40 lt\text{-}s$$




Baganoff et al. (2001)

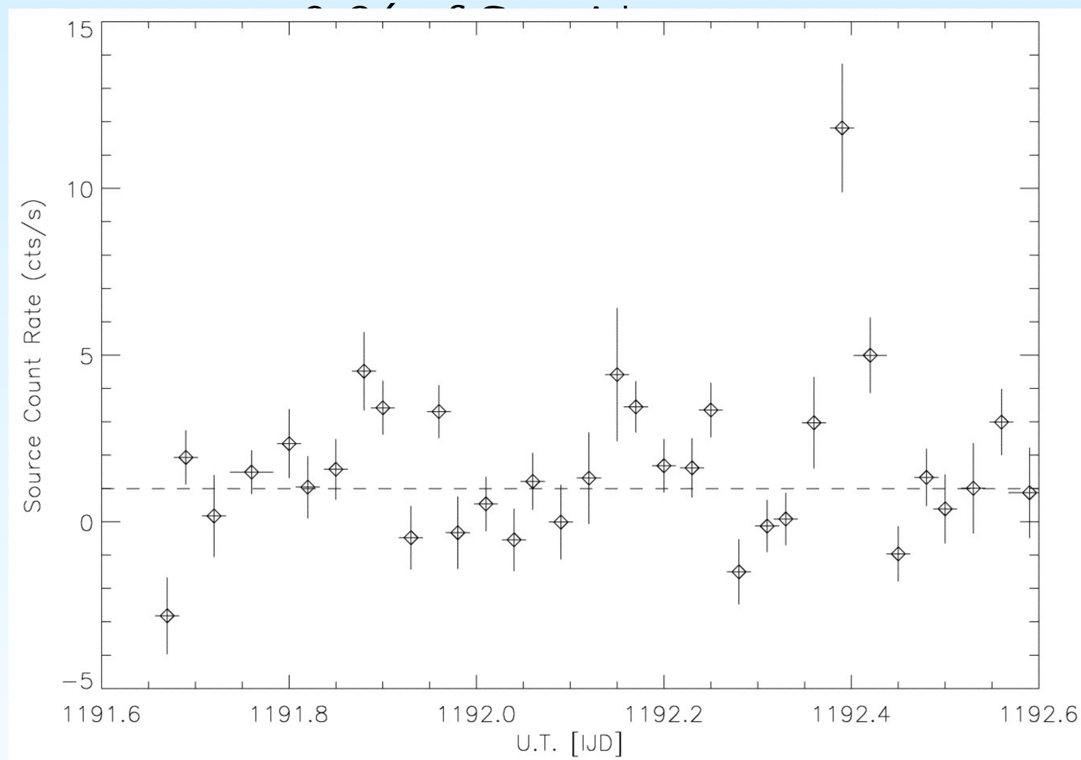



The short rise-and-decay times of the flares suggest that the radiation must origin from a region within less than tens of $r_S$




# Flaring Hard X-ray Emission from the Direction of Sgr A*

INTEGRAL observations of flaring 20-40 keV emission within




Flare lasts < 40 minutes

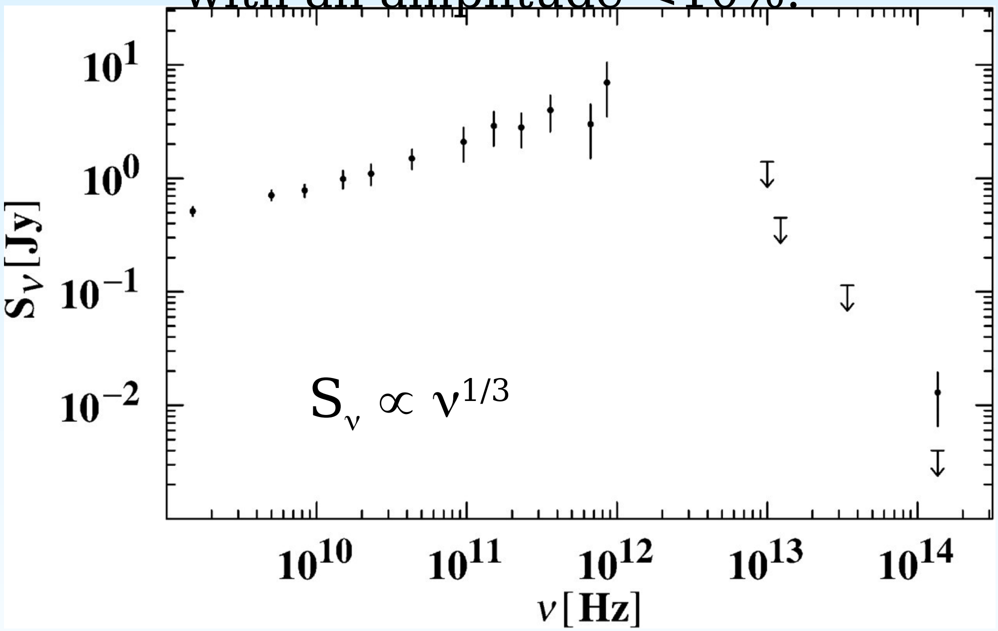
$$1 r_S = 40 lt\text{-} s$$

Bélanger et al. (2004)

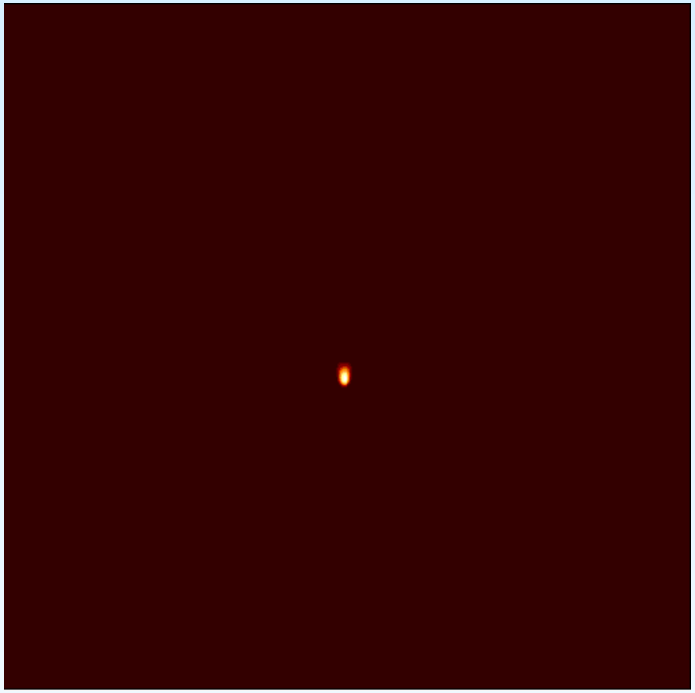
# Radio Emission from Sgr A*

Falcke et al. 2003

Radio emission of Sgr A* varies slowly on time scales of several days to a few hundred days and generally with an amplitude <10%.

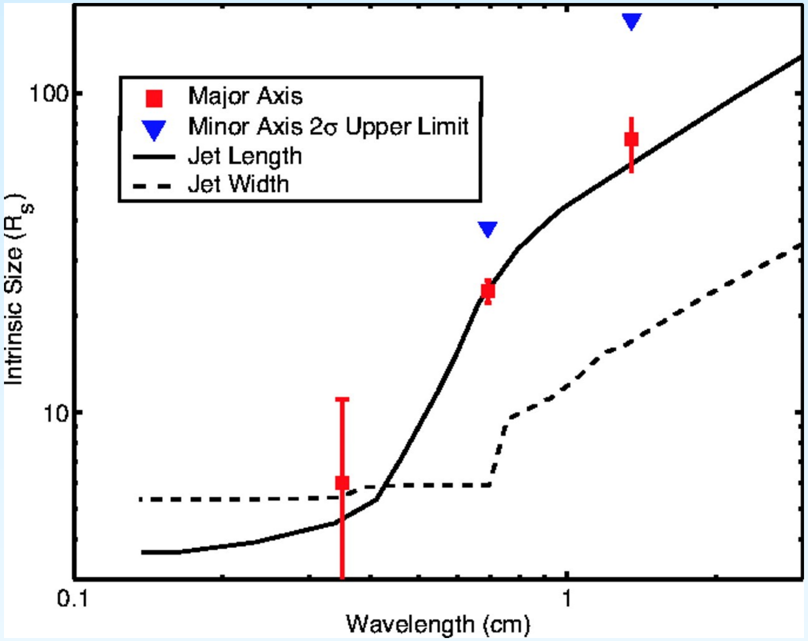



Zylka et al. 1995, Zhao et al. 2001



Radio image blurred $\propto \lambda^2$ by ionized medium, but becomes less at high frequencies (images at 5, 8, 15, 32, and 43GHz).

# Resolving Sgr A*

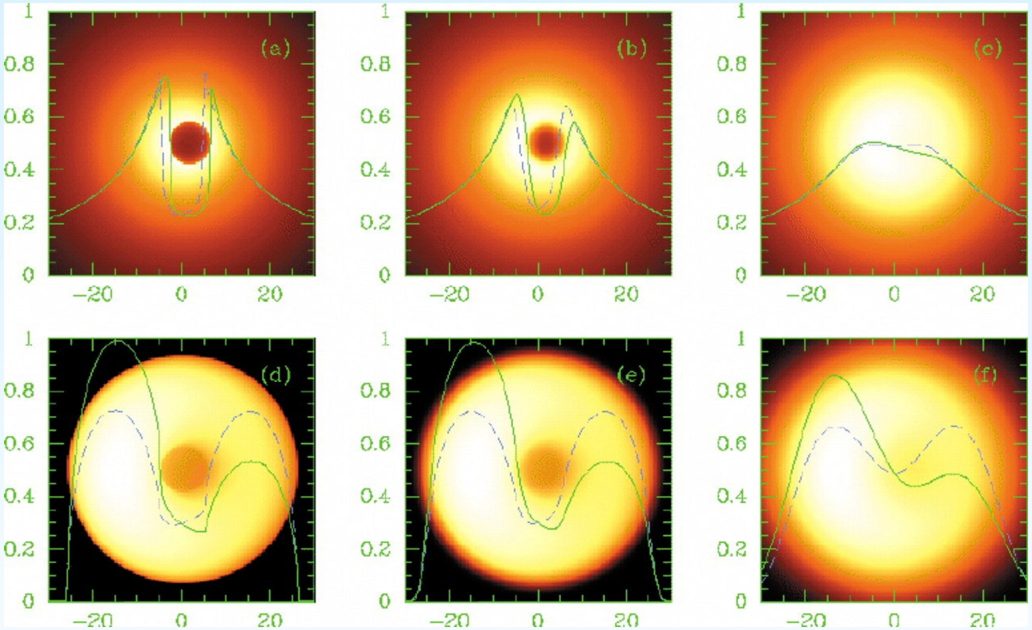



Bower et al. (2004)

Intrinsic size of Sgr A* measured using VLBA

24±2 $r_s$ at 7 mm (43 GHz)

Theoretical simulations of 1.3 cm images of Sgr A*




Falcke, Melia, & Agol (2000)

# HESS:

High Energy Stereoscopic System

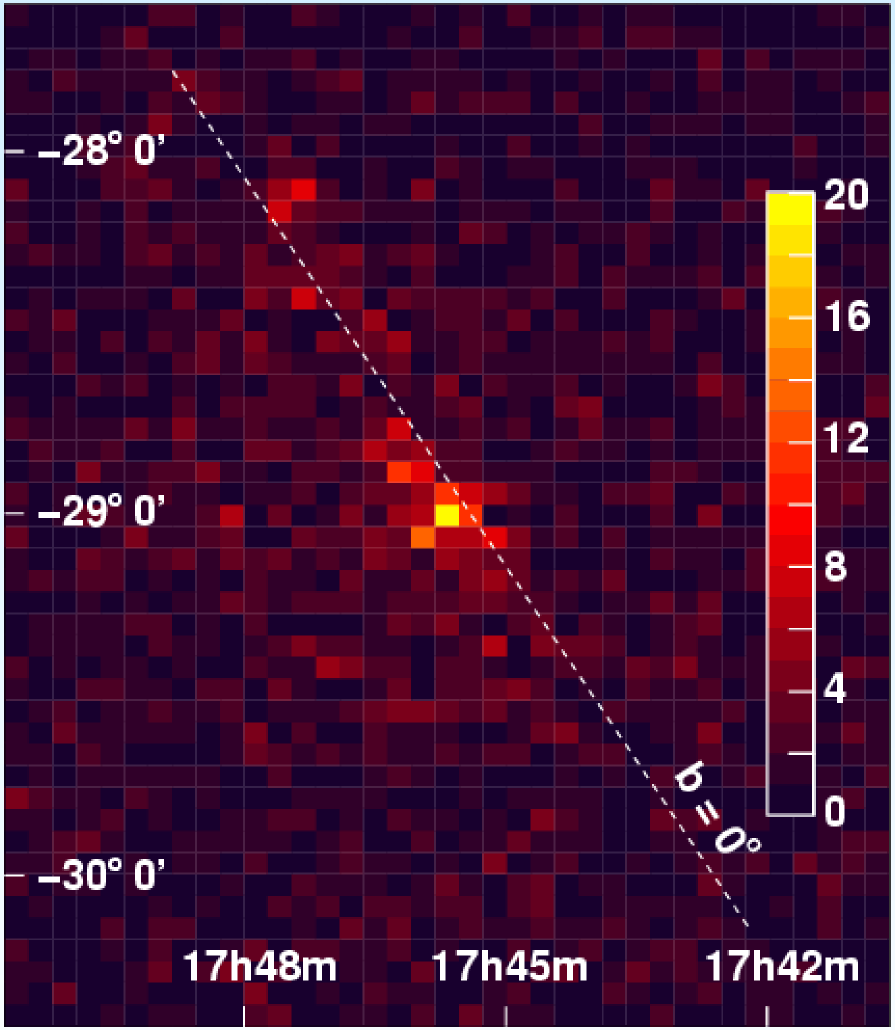
4 Telescope Array completed Dec 2003

23° 16' South Latitude

GC: -29 ° 0'

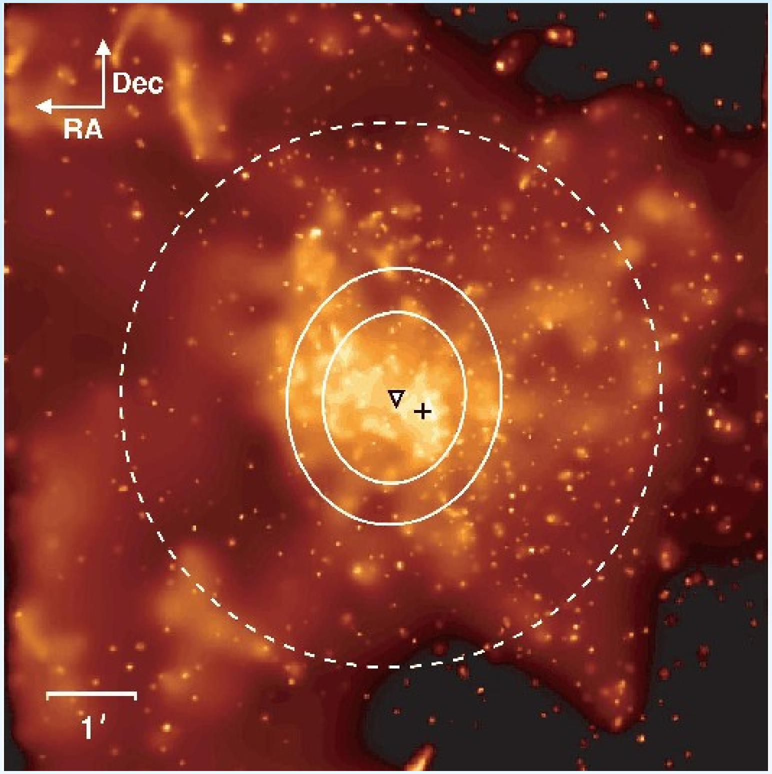
# HESS Observations of TeV Emission from Sgr A*

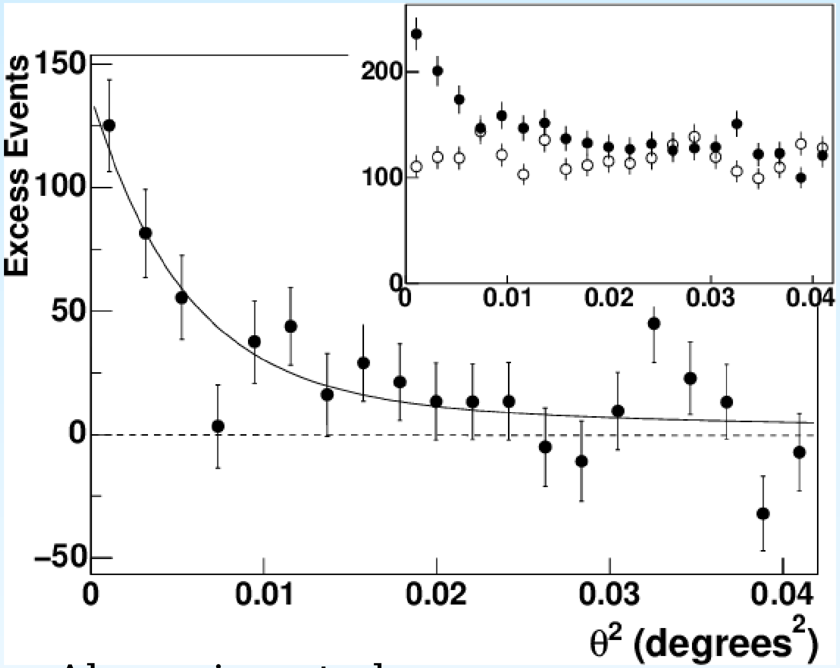
- Two observing campaigns:
  - June/July 2003 (4.7 hrs on-source)
  - July/August 2003 (11.8 hrs on-source)
- PSF ≈ 0.1°
- Angular distribution of γ rays in 3° field
- Point Source consistent with Sgr A*
  - 6.1σ in June/July
  - 9.2σ in July/Aug
- No evidence for variability between the two pointings
- Galactic Plane feature




Aharonian et al. (2004)

# HESS Measurements of TeV Angular Distribution



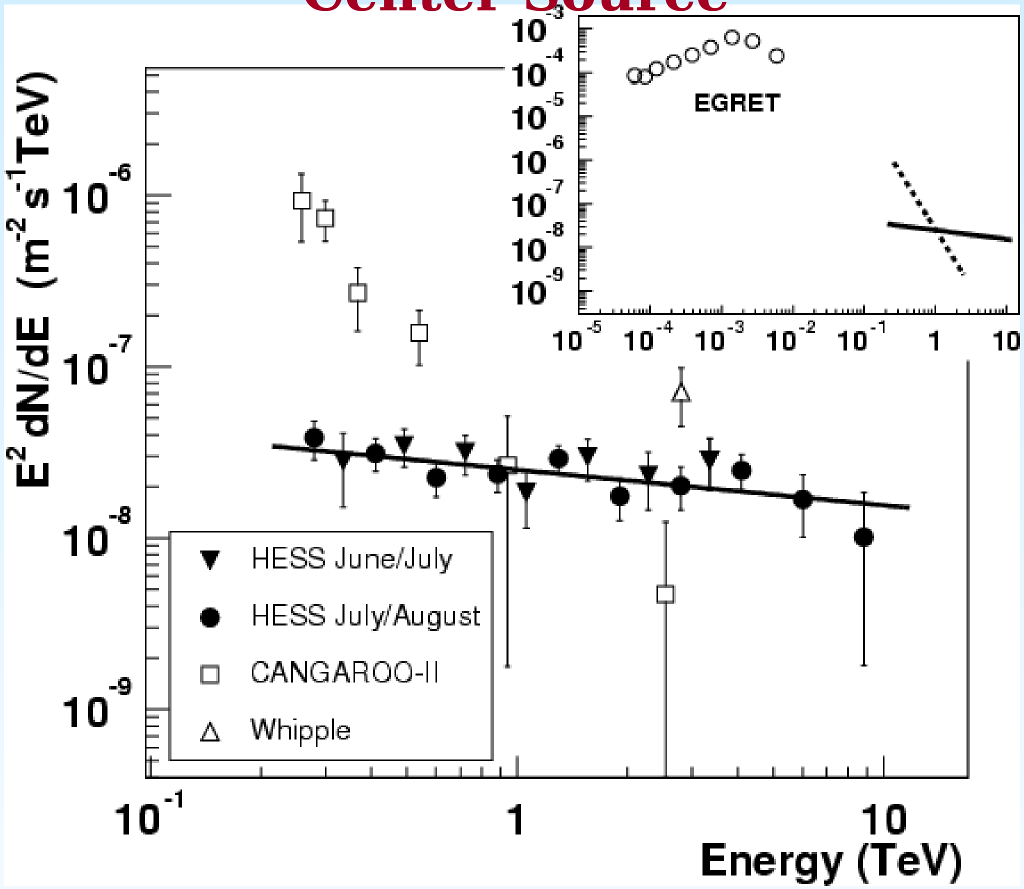

Aharonian et al. (2004)

Angular distribution of γ rays

Upper limit to source size = 3' ↔ 7 pc

Center of gravity of γ rays (triangle), 68% and 95% confidence regions for source position (solid ellipses), and 95% confidence of rms source size (dashed ellipse), superimposed over 8.5'×8.5' Chandra X-ray map.

# HESS Measurements of TeV Spectrum of Galactic Center Source

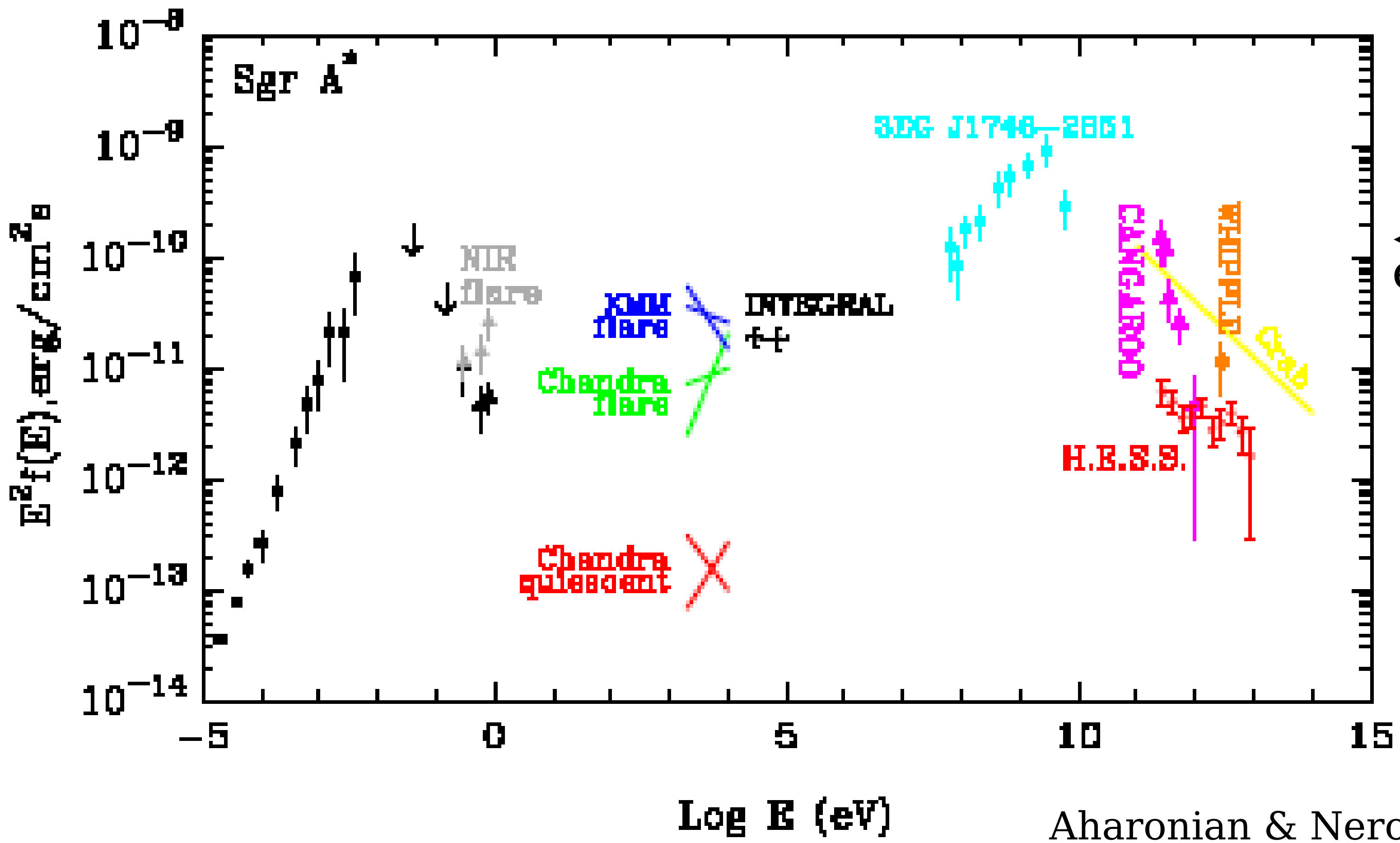



$E^2$dN/dE spectrum for June/July, July/August campaigns

$dN/dE \propto E^{-2.21\pm0.21} \times 10^{-8}$ $m^{-2}$ $s^{-1} TeV^{-1}$ ( ≈5% of the Crab)

In agreement with Whipple (Kosack et al. 2004); disagrees with Cangaroo-II (Tsuchiya et al. 2004)

# Multiwavelength Observations of Galactic Center Region




$\sim 10^{36}$ ergs $s^{-1}$

Aharonian & Neronov (2004)

EGRET emission displaced from direction to GCBH

## Previously Proposed Models for TeV Emission

1. $\gamma$ rays from $\pi^0$ production from secondary nuclear production of cosmic rays (possible accelerated by Sgr A West SNR)

2. Annihilation of supersymmetric dark matter particles

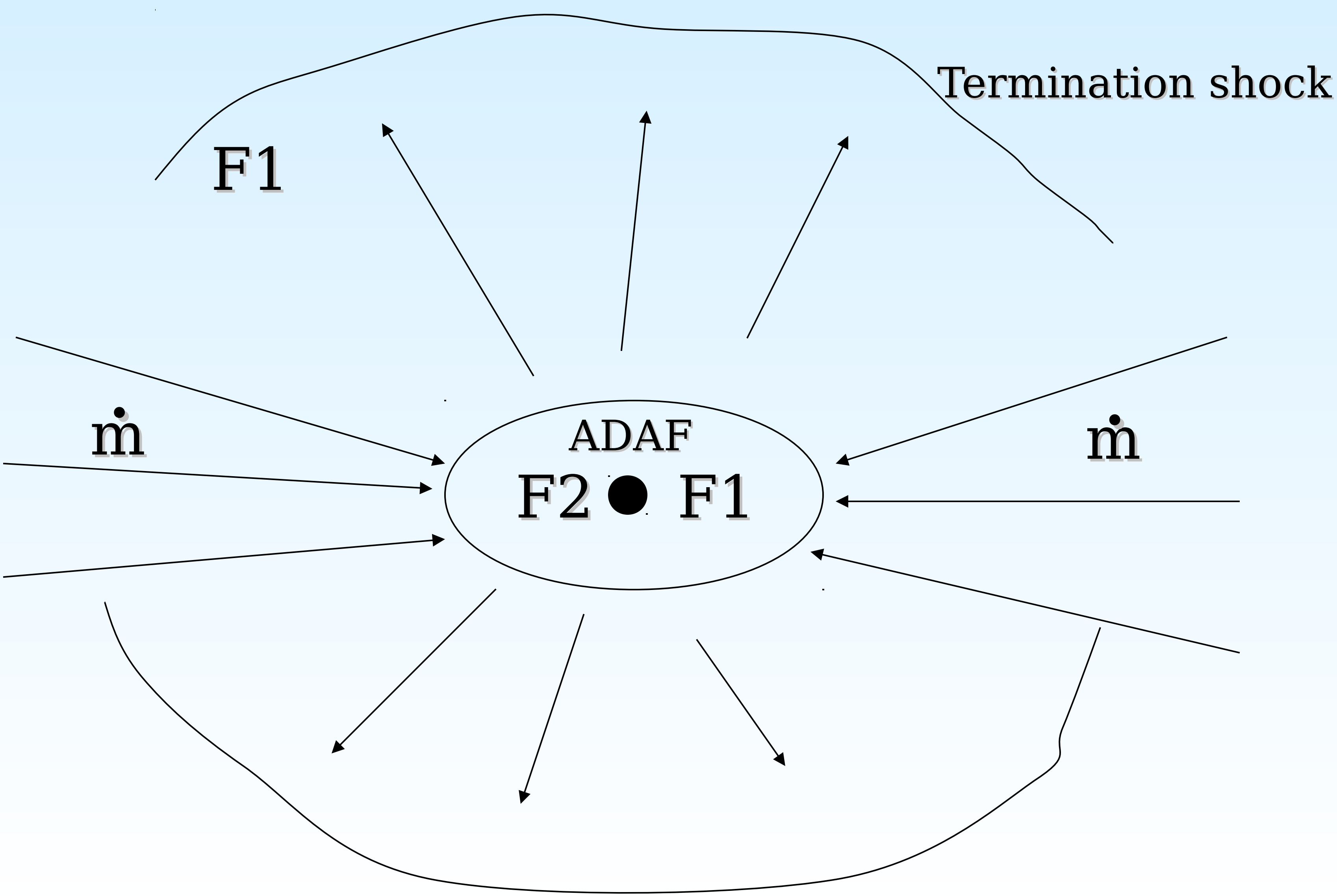
   (Requires neutralinos of mass > 4-10 TeV)

3. Jet-ADAF model (acceleration in the inner jet from shocks; would expect significant variability)

4. Proton curvature radiation

5. TeV jet models (where is the jet?)

# TeV Radiation from the Galactic Center Black-Hole Plerion



# Accretion Physics in the ADAF/ADIOS Regime

Advection-dominated accretion flow (ADAF) model for compact objects accreting at low Eddington accretion rate

$$\dot{m} \equiv \eta_{BH} \dot{M} c^2 / L_{Edd}$$

Radiant luminosity at the level

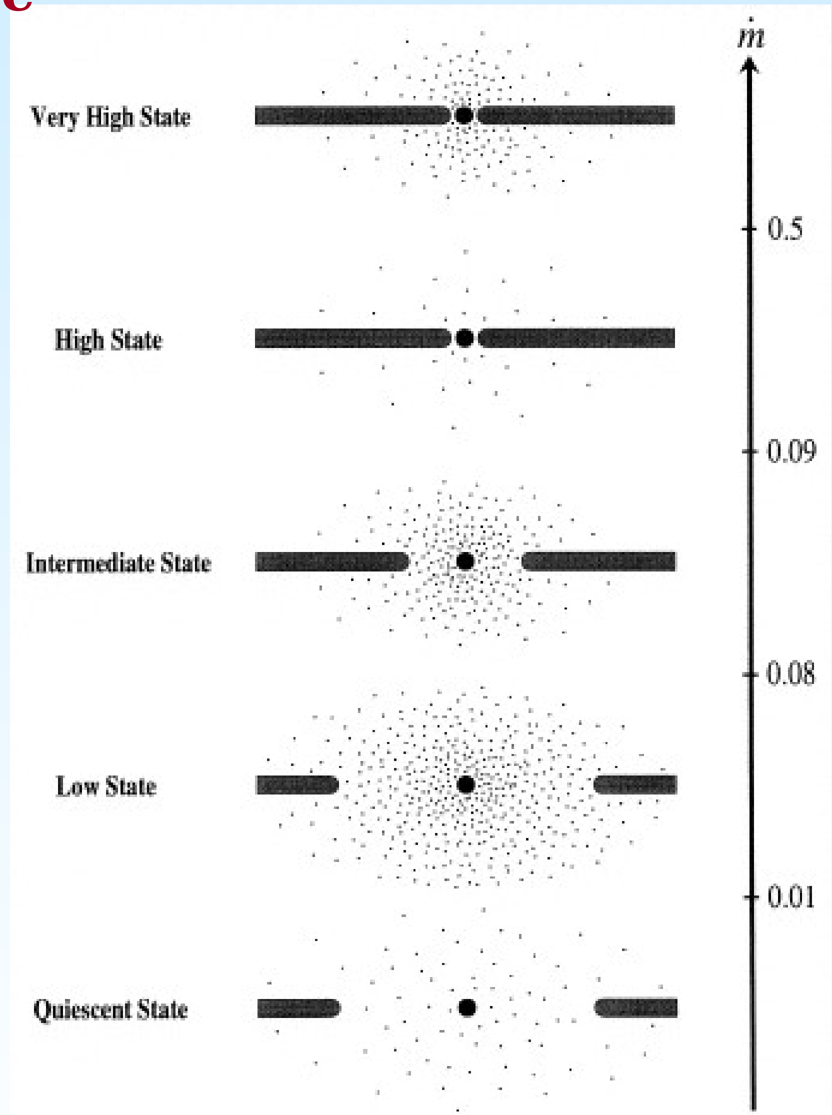
$$L_{rad} = \dot{m} L_{Edd} (\dot{m}/\dot{m}_*),$$

$$\dot{m}_* \approx 0.1$$

$(\dot{m}/\dot{m}_*)$ is fraction of accretion power that is advected into black hole or convectively escapes

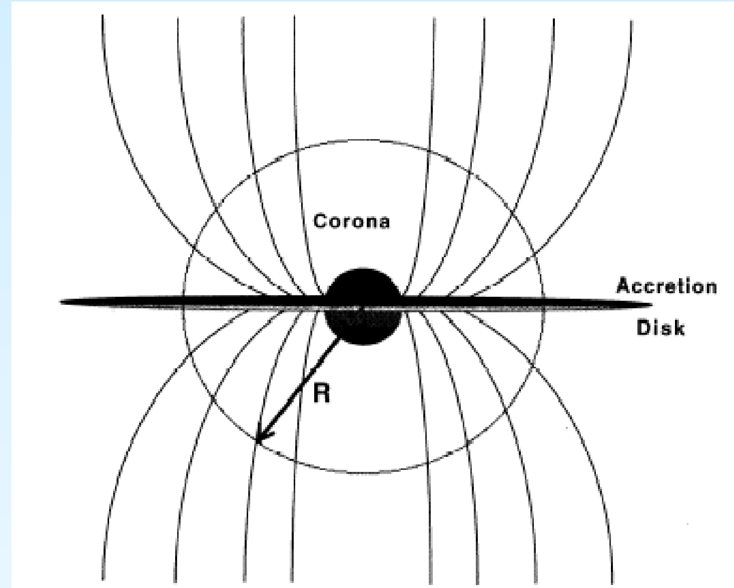
$$L_{th} = L_{rad} = 10^{36}\, ergs\, s^{-1} \Rightarrow$$

$$\dot{m}_{GCBH} \approx 1.5 \times 10^{-5}$$




Esin, McClintock, & Narayan (1997)

# Second-order Fermi Acceleration in the ADAF




No optically thick accretion disk

Second-order stochastic Fermi acceleration for radio-sub mm emission

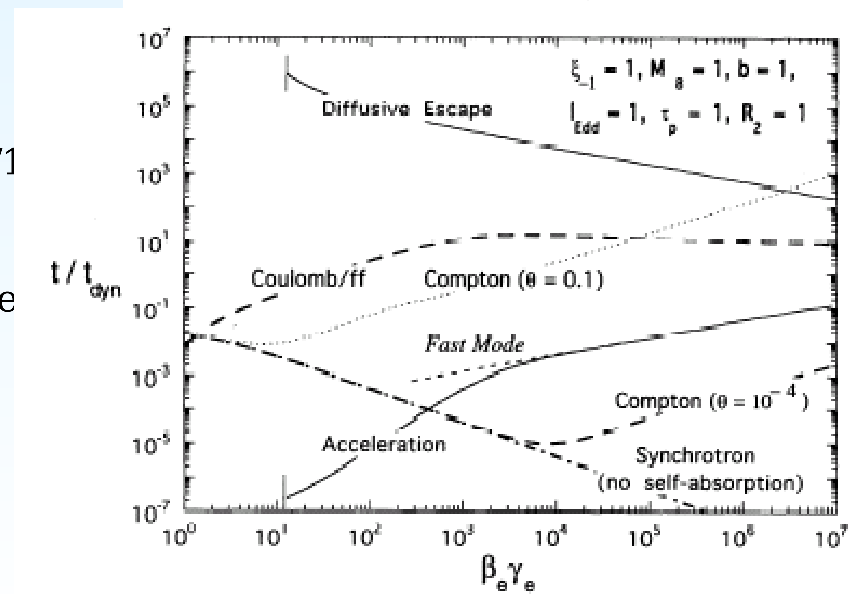
$$\frac{B^2}{8\pi} = \varepsilon_B \left(\frac{\eta_{BH}\dot{M}c^2}{4\pi R^2 c}\right) \Rightarrow B(G) \approx 30\,\varepsilon_B^{1/2} L_{36}$$

for a region of size 20 $r_S$

Equating acceleration rate of electrons by Whistler turbulence to synchrotron loss rate:

$$\gamma_0 \approx 200 (\xi_{-1}\varepsilon_{B,-1})^{1/3} L_{36}^{1/2} \left(\frac{\tau_T}{2\times 10^{-4}}\right)^{-11/1}$$

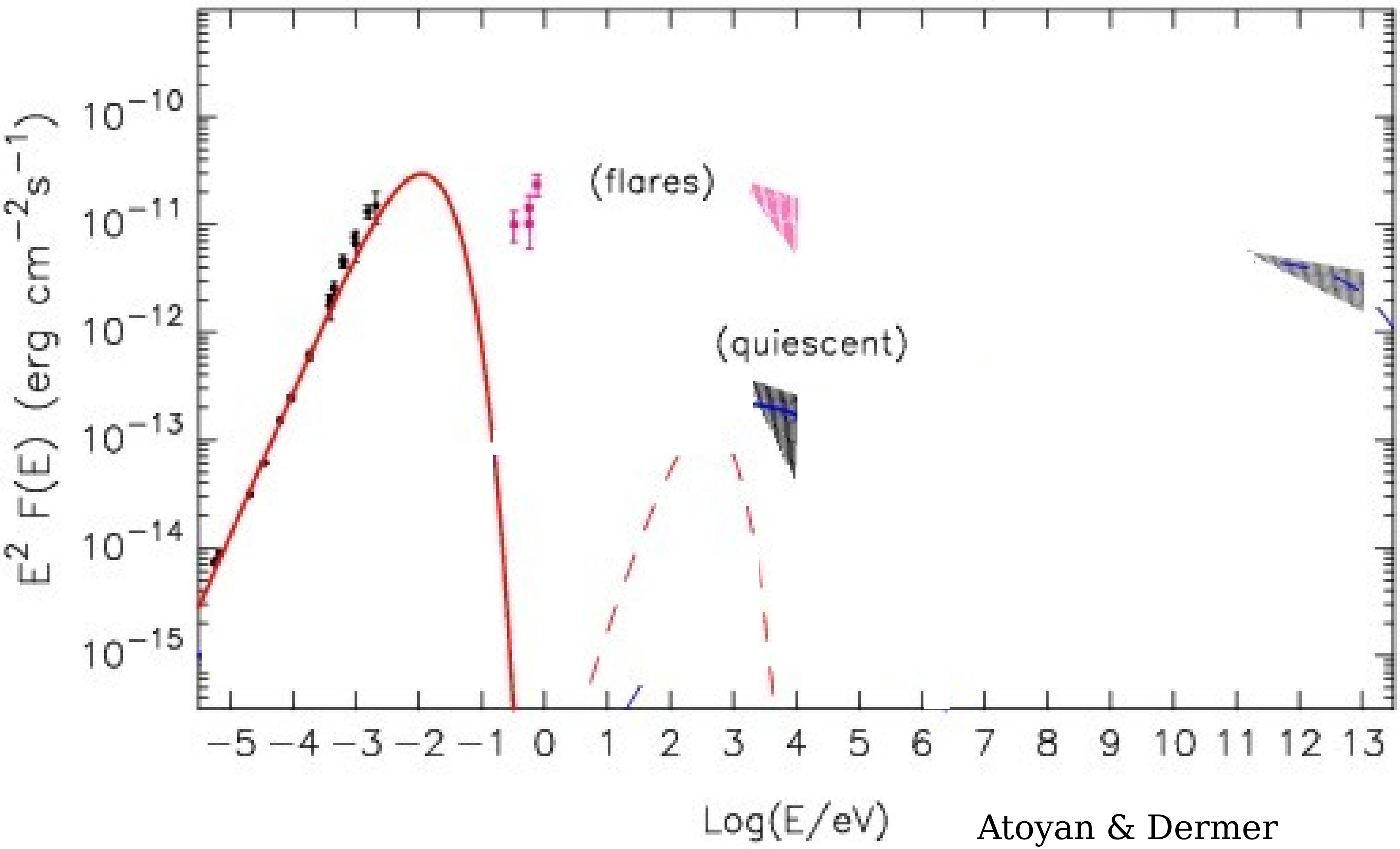
Dermer, Miller & Li 1996; Liu, Petrosian, & Me
2004




Steady-state electron spectrum:

$$N(\gamma) \propto \gamma^2 \exp(-\gamma/\gamma_0)$$

# Stochastic acceleration model for radio/sub-mm emission




Atoyan & Dermer (2004)

## The Black Hole Plerion

Particle escape by convective outflow in advection-dominated inflow-outflow source (ADIOS) extension (Blandford & Begelman 1999) of ADAF model.

Assume a wind power

$$L_{wind} = 10^{37} L_{37}\, erg\, s^{-1}$$

With speed $v_{wind} \approx c/2$ directed into solid angle $\Omega \approx 1$ sr

Wind terminates at a subrelativistic shock at

$$R_{shock} \approx 3 \times 10^{16} L_{37}^{1/2}\, \Omega_w^{-1/2}\, cm$$

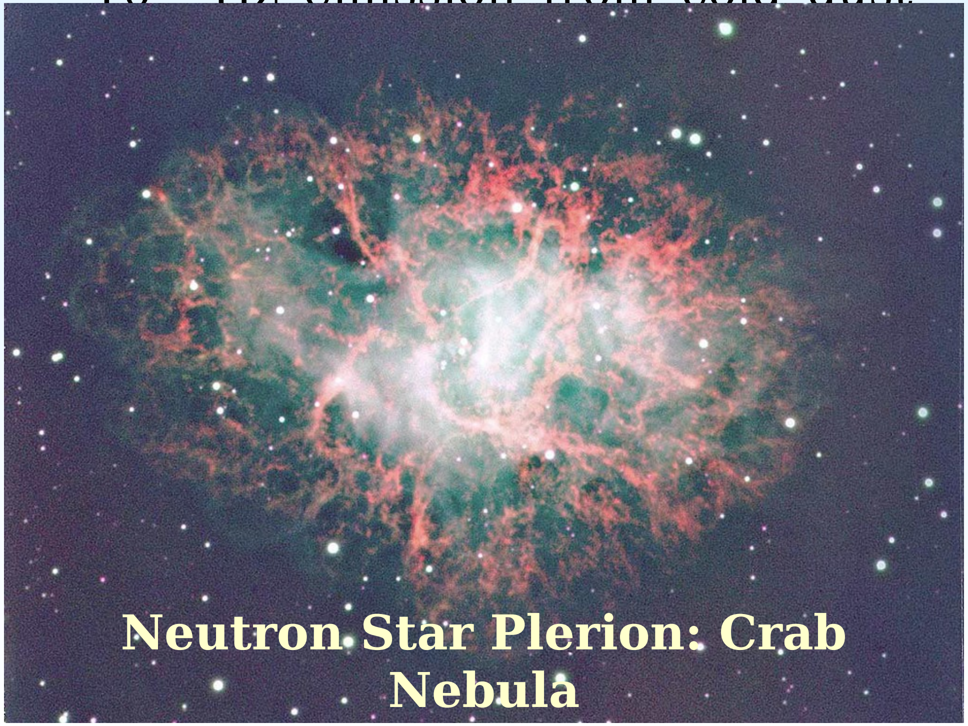
found by equating thermal gas pressure with energy density of wind

Electrons and protons accelerated by first-order (shock) Fermi acceleration.

Electrons emit X-ray synchrotron radiation to form quiescent X-ray emission

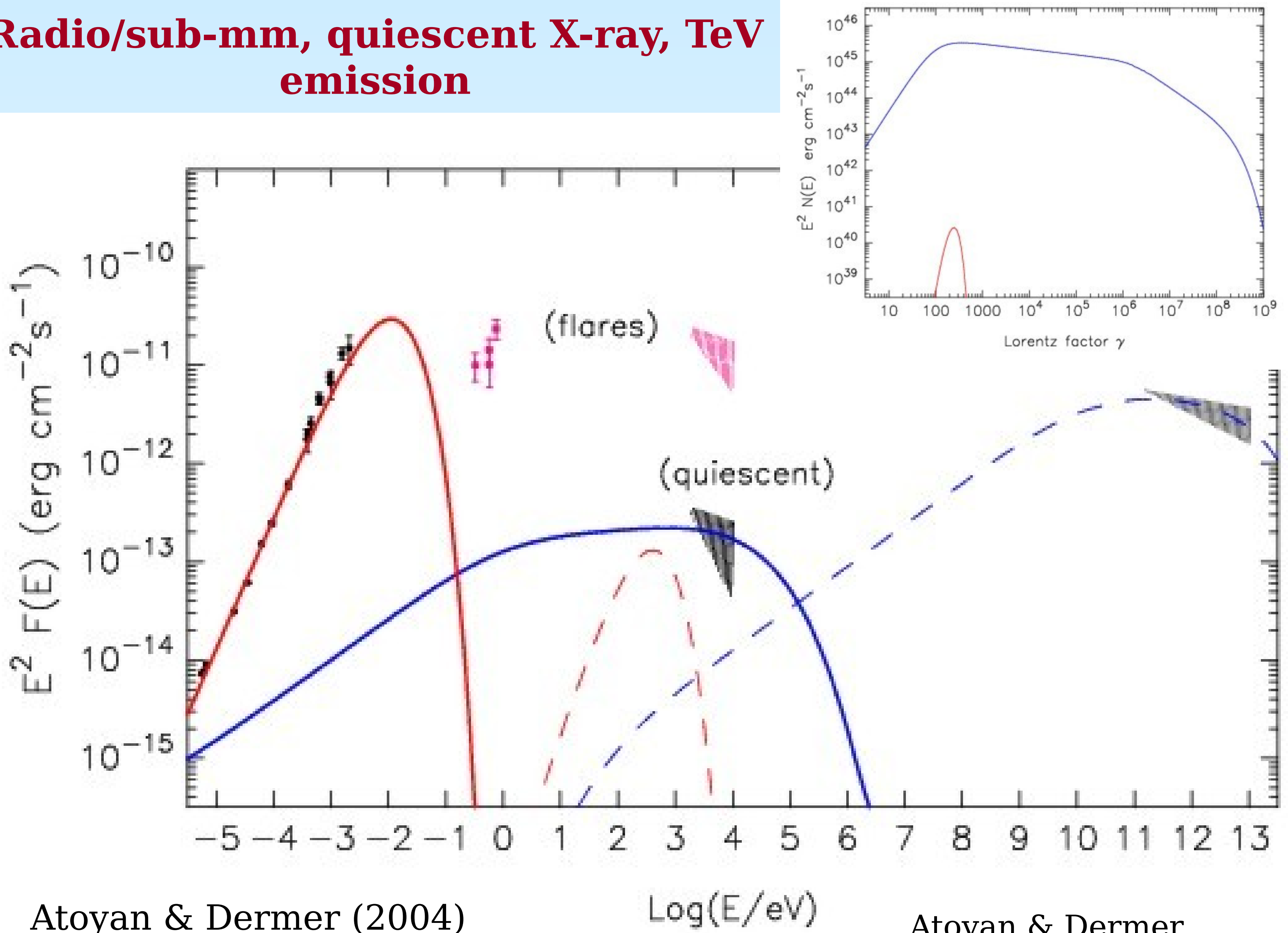
and Compton scatter

- ADAF emission
- $10^{13}$ Hz emission from cold dust



**Neutron Star Plerion: Crab Nebula**

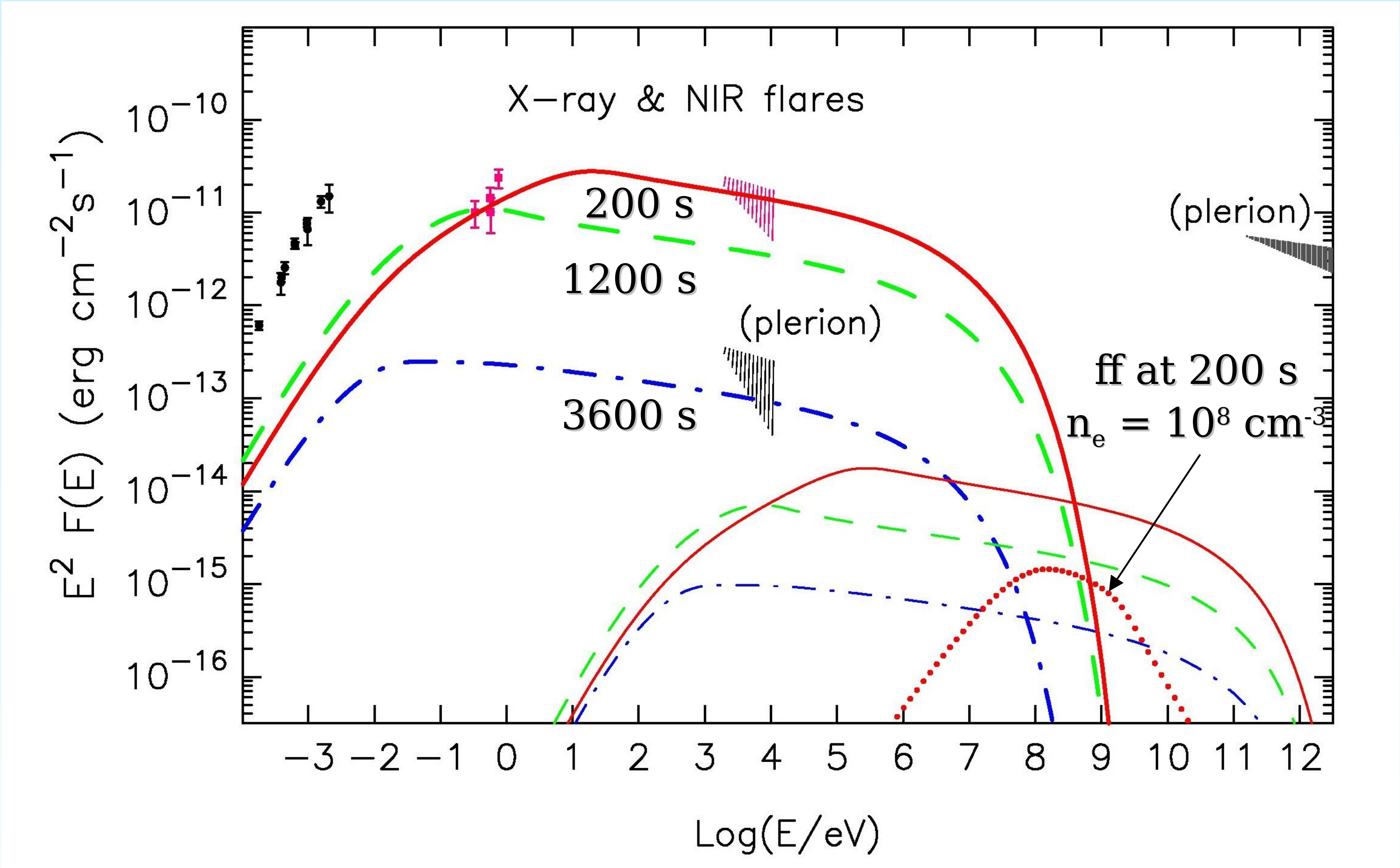
# Radio/sub-mm, quiescent X-ray, TeV emission




Atoyan & Dermer (2004)

Atoyan & Dermer (2004)

# Flaring Emissions from Inner Region

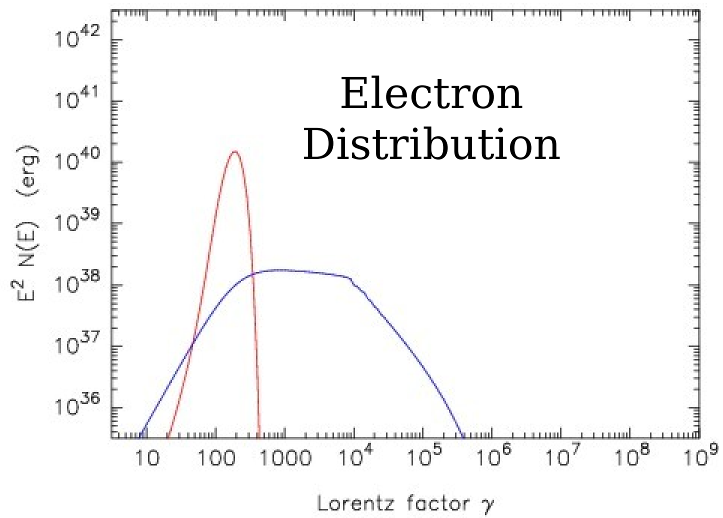


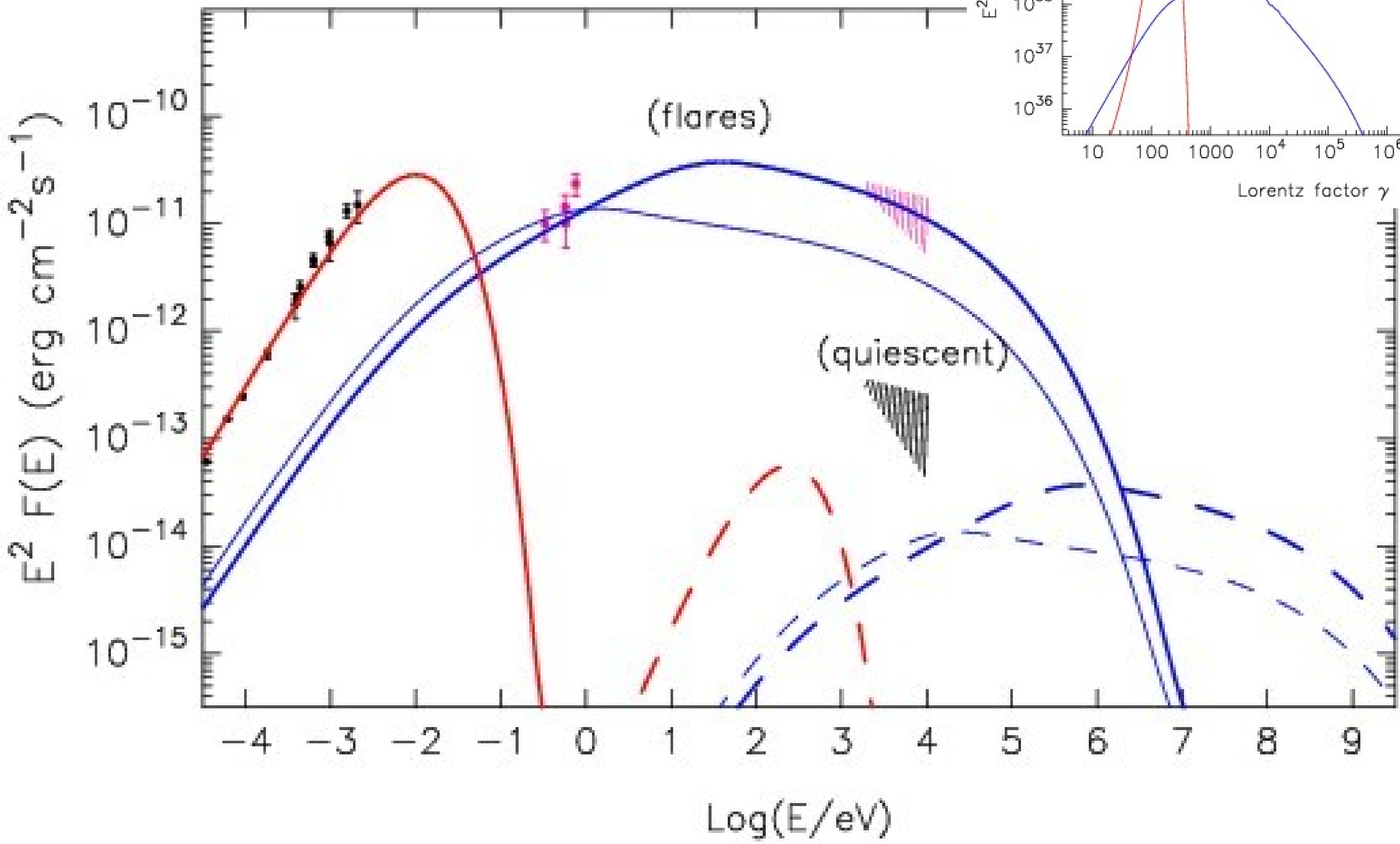

Flares from instabilities in accretion flow that form shocks at few $r_S$

First-order Fermi shock acceleration injects electrons with $\gamma < 10^6$, -2.2 injection index

Explains X-ray/NIR flares and short variability timescales from cooling and expansion

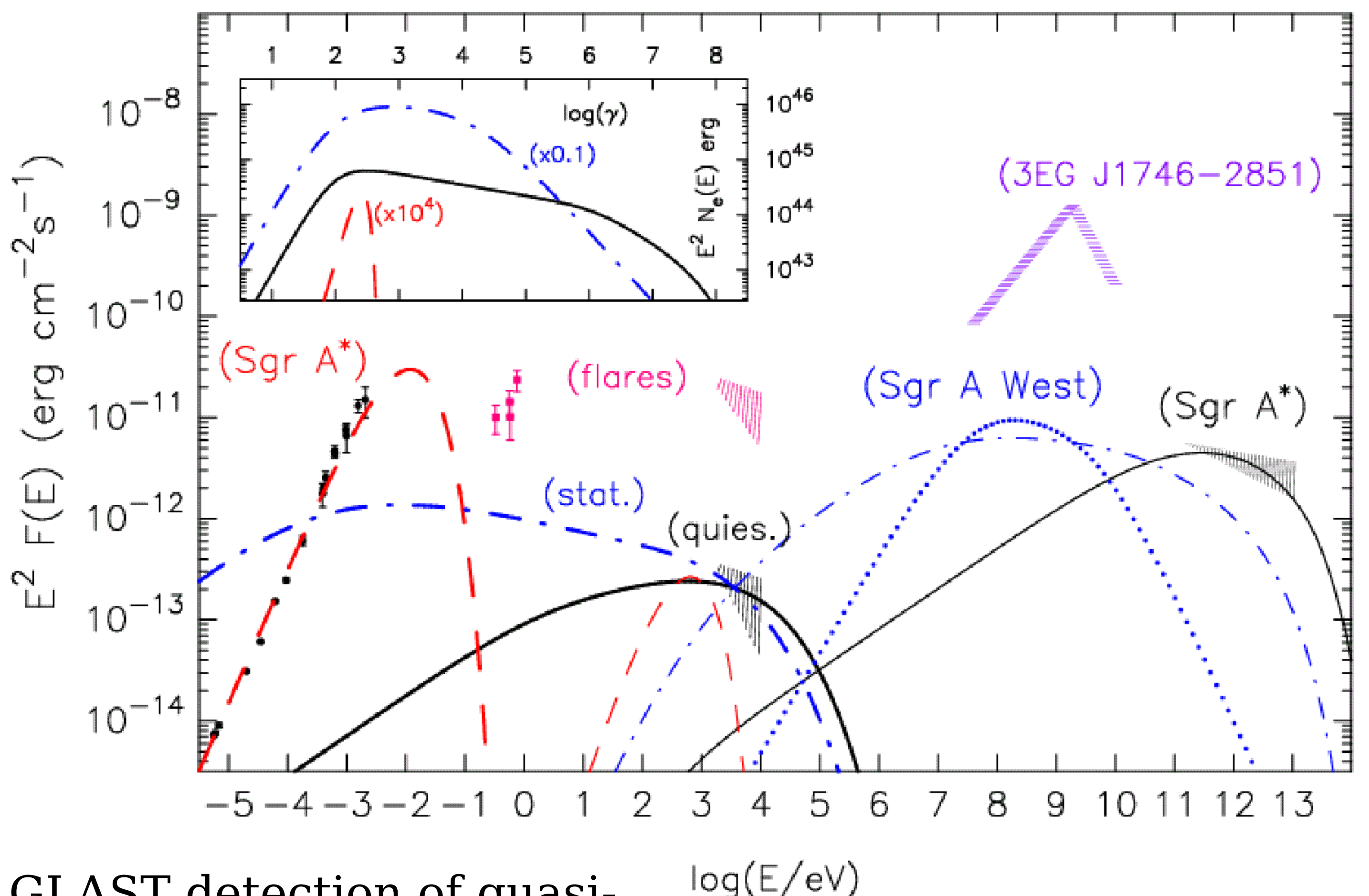
# Multiwavelength Emission from Sgr A*




Very weak > 100 MeV $\gamma$-ray emission

# Galactic Center Black Hole Emission: Sgr A* ADAF + Black-Hole Plerion + Sgr A West, a black-hole remnant



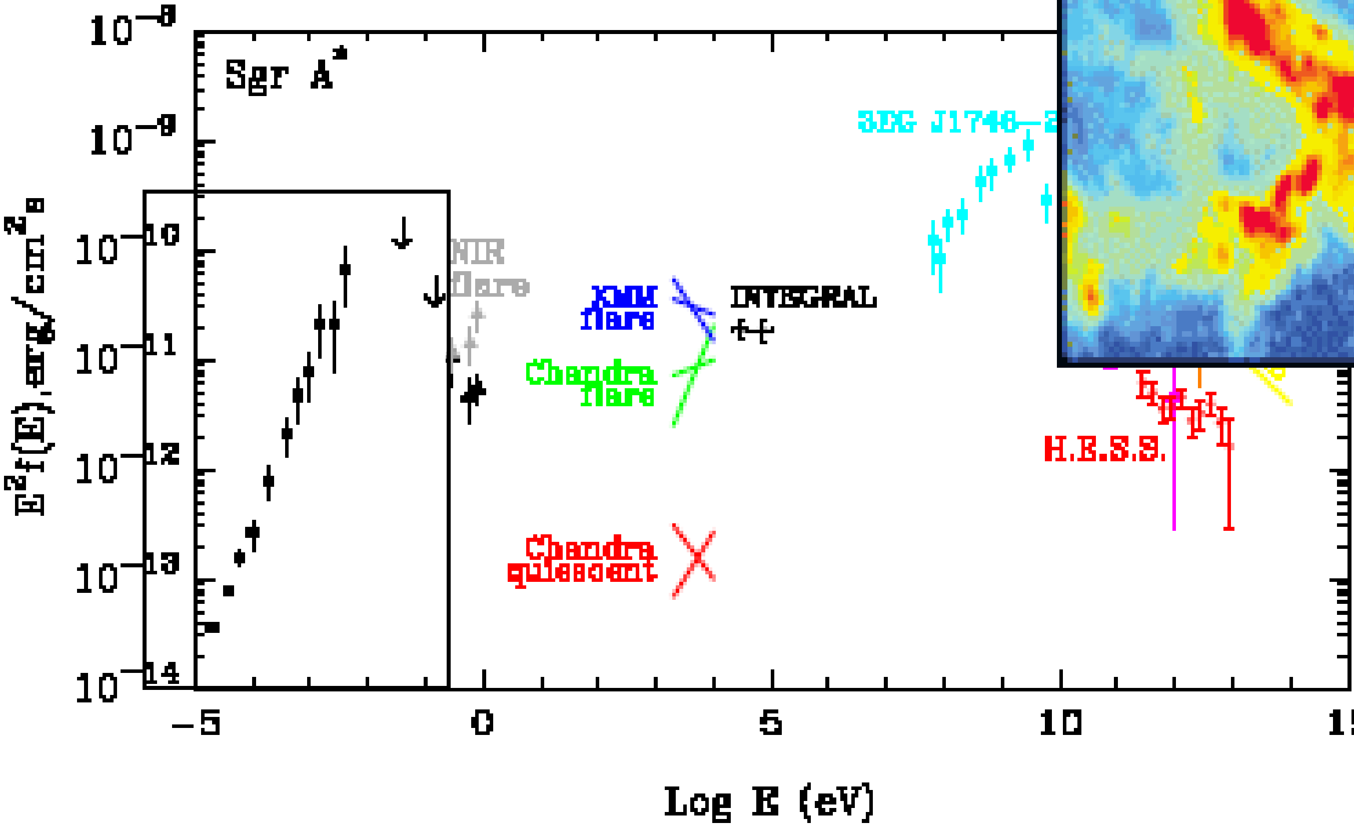

Predict GLAST detection of quasi-stationary Compton and bremsstrahlung fluxes from pc-scale plerion.

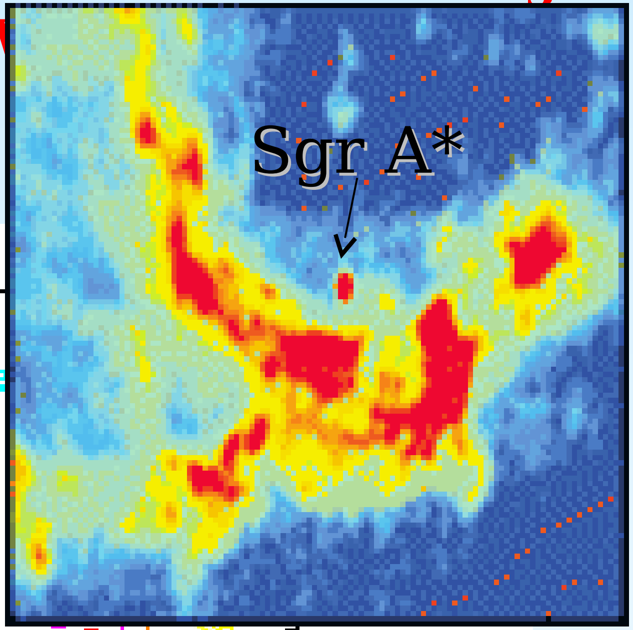
Propagation of GeV electrons power Sgr A West

EGRET emission from young pulsar

# Multiwavelength Observations of Sgr A*

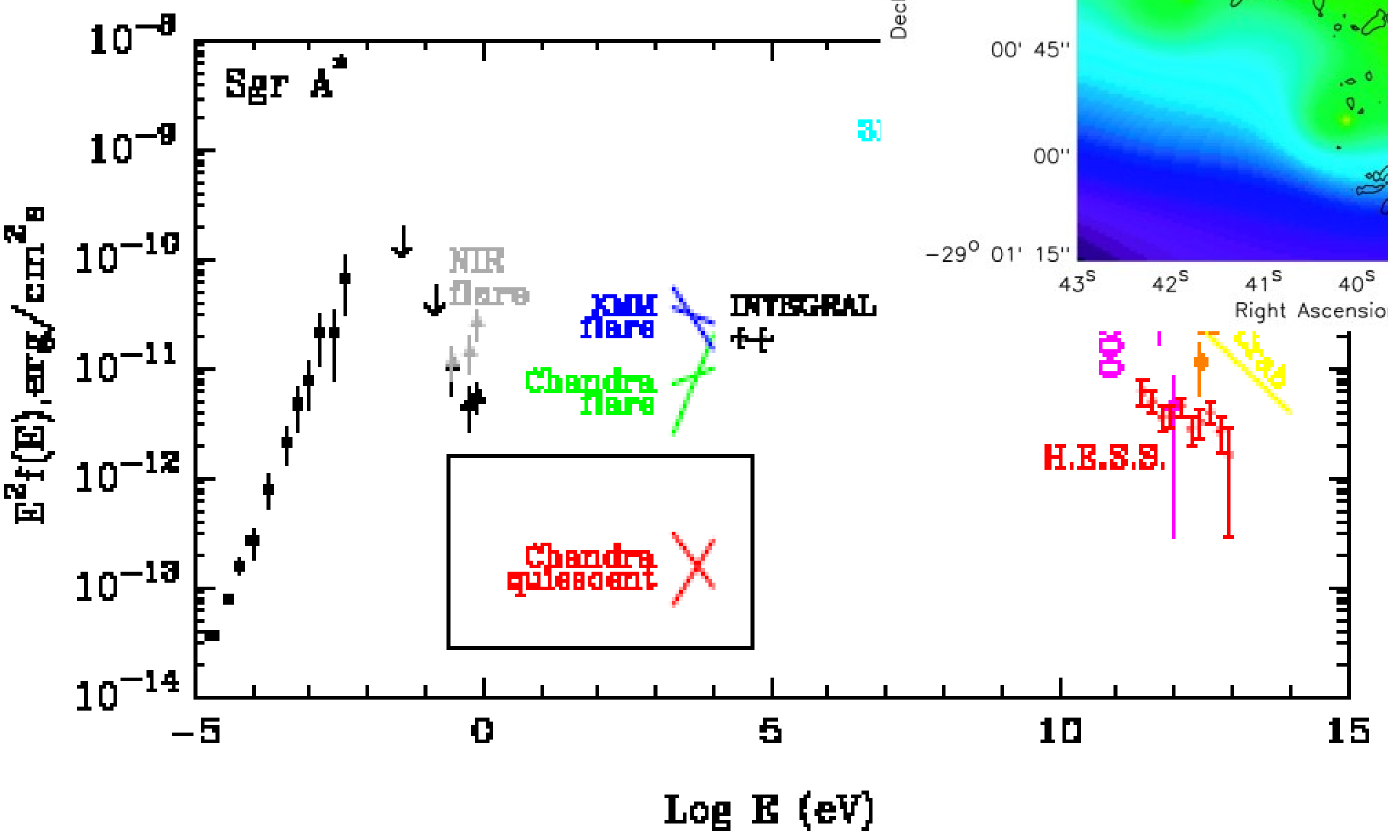
**2 cm VLA radio of Sgr A**

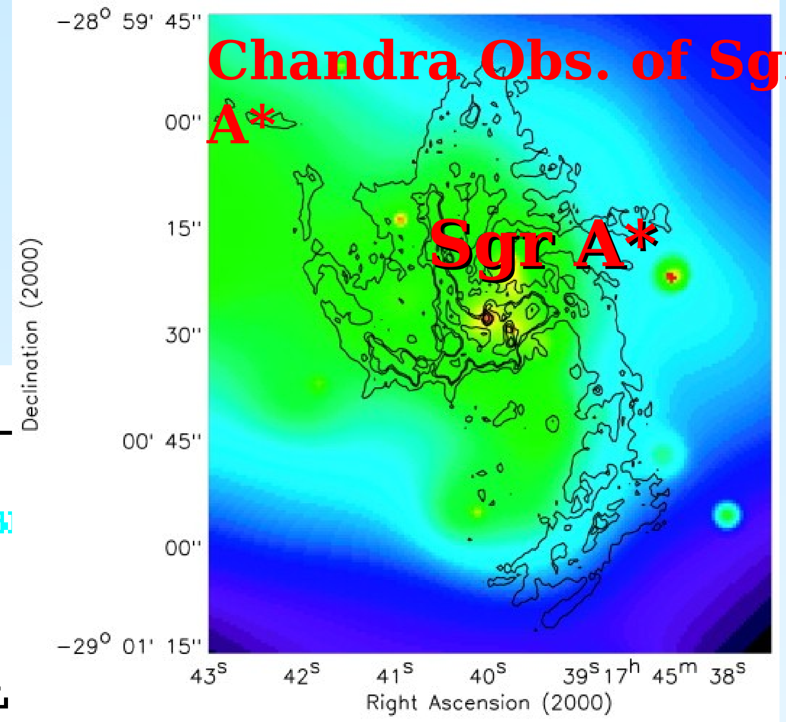



(Yusef-Zadeh & Wandle
1993)

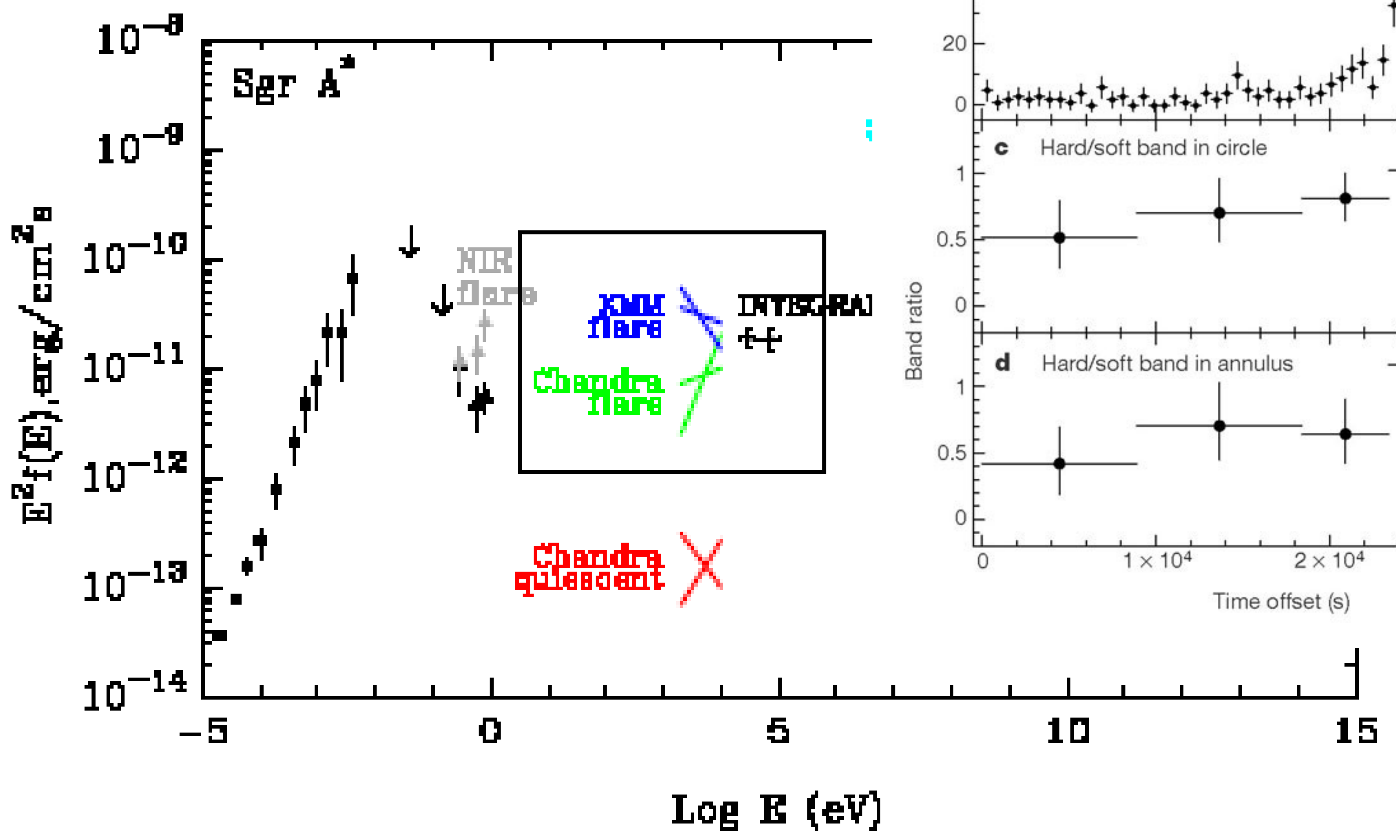
# Multiwavelength Observations of Sgr A*

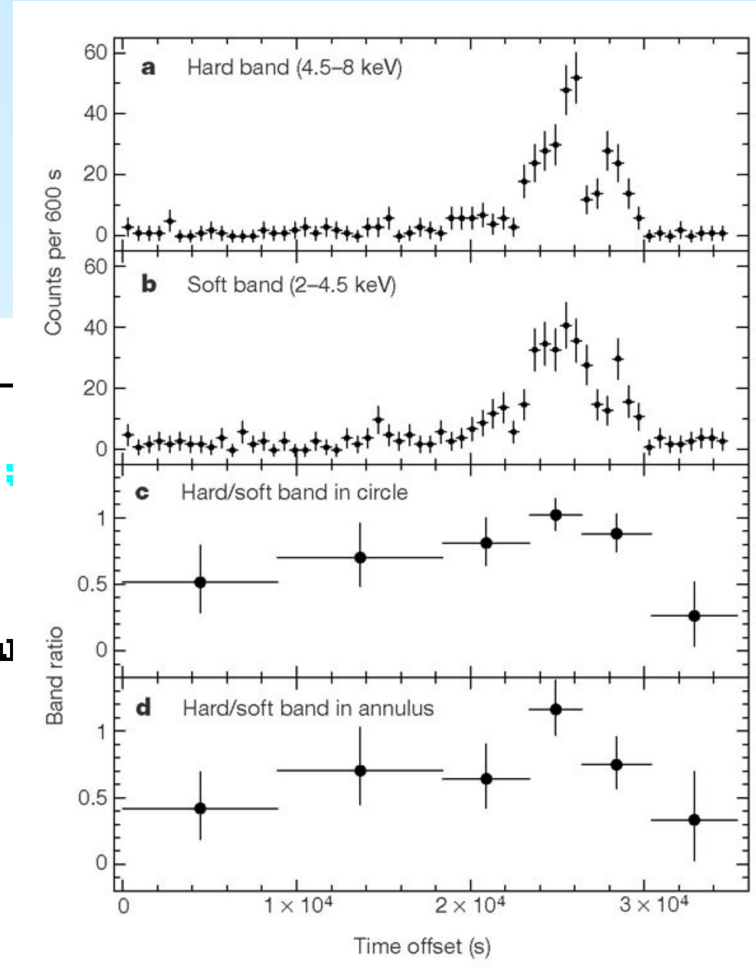



Baganoff et al. 2003

# Multiwavelength Observations of Sgr A*

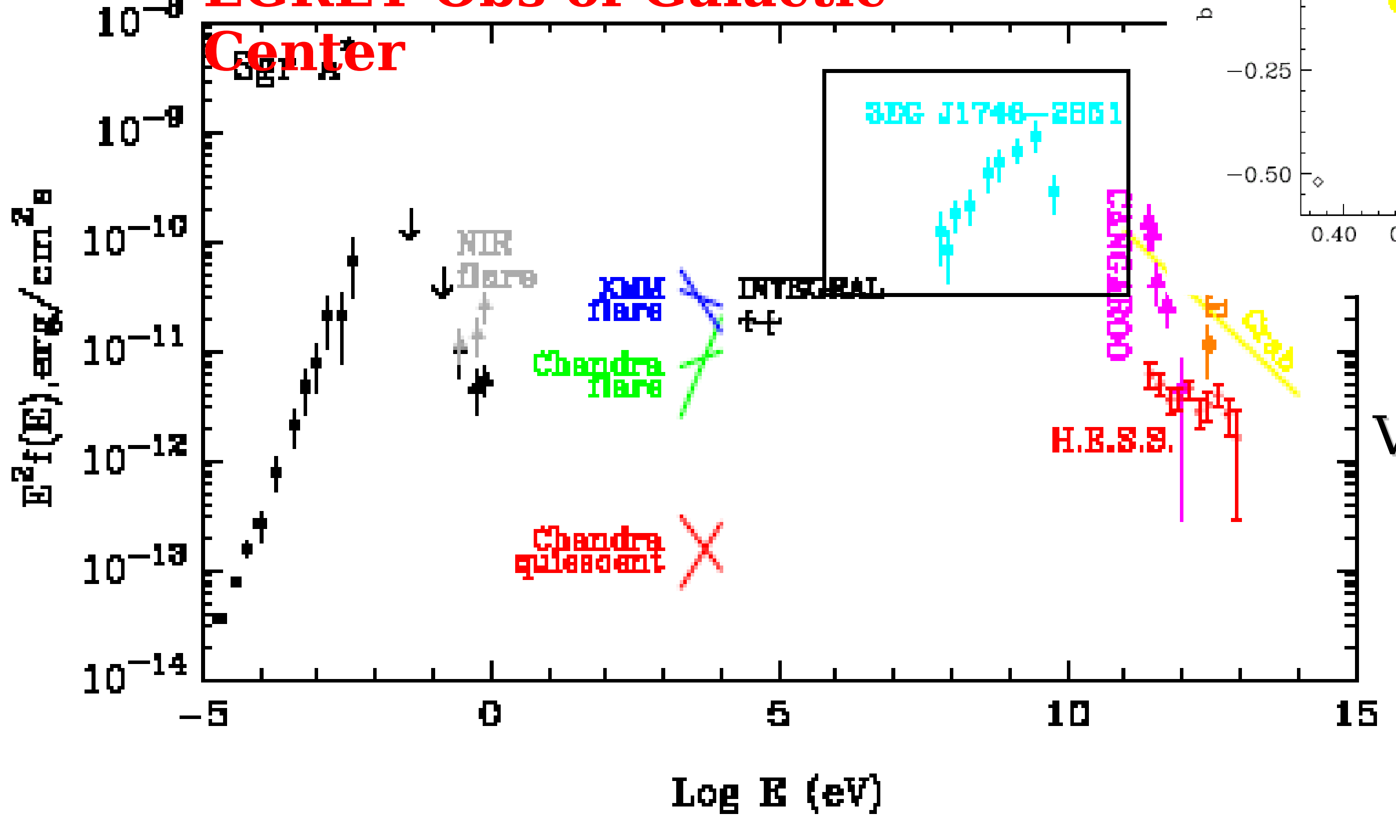


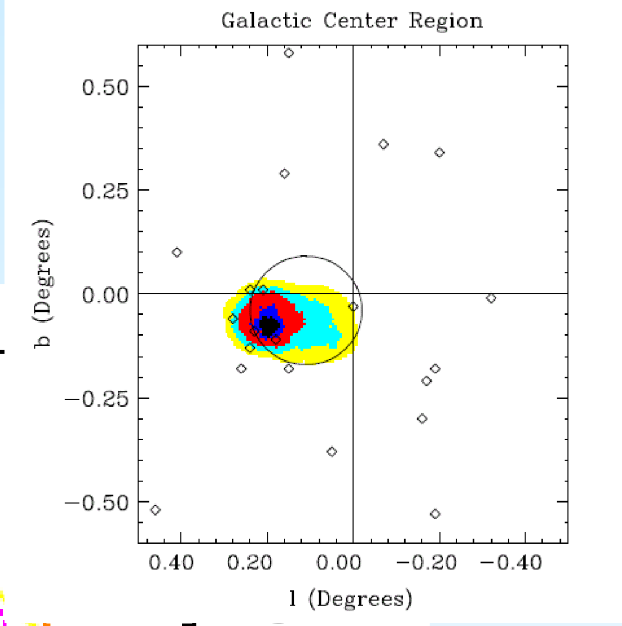




Baganoff et al. 2001

# Multiwavelength Observations of Sgr A*

## EGRET Obs of Galactic Center




Vela-like Pulsar?

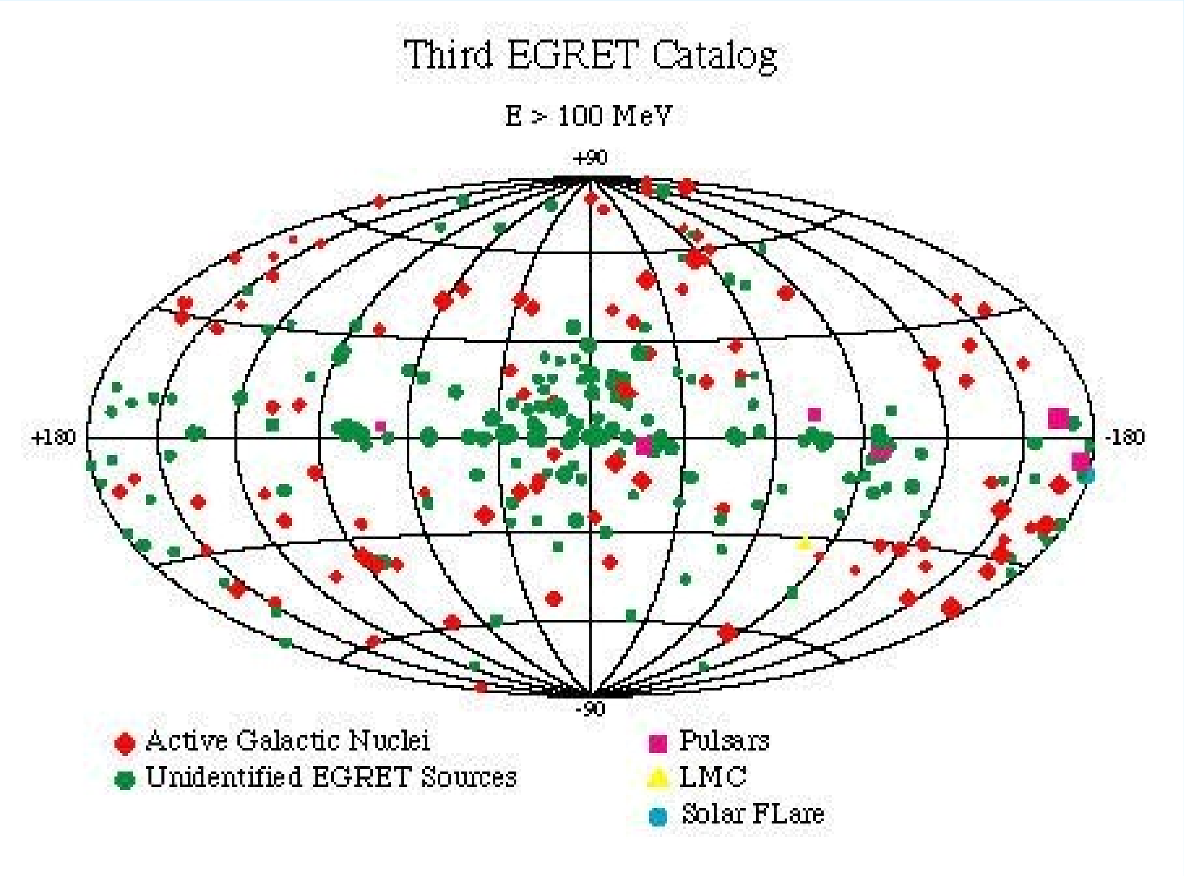
EGRET emission displaced from direction to GCBH

Dingus and Hooper 2002;
Pohl 2005

# Summary

1. TeV radiation from Galactic Center Region: Important Discovery from next generation Imaging Air Cherenkov Telescopes
2. Observations imply two emission regions:
    - (i) Inner region near black hole
    - (ii) Black hole plerion at the termination shock
3. New insights into black-hole accretion in the extreme ADAF regime for GCBH; advection and convective outflow from central accretion flow
4. X-ray flares are synchrotron emission within $\sim 10\ r_S$ of GCBH
5. Quasi-stationary TeV emission (southern hemisphere Crab)
6. TeV $\gamma$ rays made by black-hole plerion, first of a new class of nonthermal emitters

# Unidentified EGRET/TeV Sources




Plerions from Binary Compact objects accreting << $L_{edd}$

Isolated accreting black holes

Winds and plerions associated with blazars?

# Black Hole Archaeology

$$M_{BH}, z, L_{rad} \Rightarrow \ell = L_{rad} / L_{Edd}$$

Measure $M_{BH}$ from γ-ray variability

Light crossing time-scale: $10^4\ M_9$ sec

$L_{iso}$ from γ-ray and multi-wavelength observations

Jet opening angle: variability analysis, multiwavelength modeling

- Stellar velocity dispersion
- Reverberation mapping
- Bulge/BH relation

# The life history of massive and supermassive BHs

**(within ADAF framework)**